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Nutritional status of cocoa in Papua New Guinea

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Paul N. Nelson, Michael J. Webb, Suzanne Berthelsen, George Curry,
David Yinil and Chris Fidelis

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Cover: Sampling and sieving soil at survey site 2 for analysis of soil characteristics (Photo: Mike Webb)

Foreword

Demand for chocolate, 'the food of the gods', is rising inexorably, creating opportunity for countries like Papua New Guinea (PNG), which has ideal growing conditions for cocoa in the coastal lowlands. PNG produces less than 2% of the world's cocoa, but the crop is extremely important for many people's livelihoods. An estimated 151,000 households rely on cocoa as one of their principal sources of income. Cocoa from PNG is known for its good and consistent quality, with particular flavour, high fat content and large beans.

Cocoa was introduced to PNG in 1880 by German traders, and the industry developed slowly until the 1950s when the Australian administration promoted its cultivation among villagers. It is now one of the four major export tree crops cultivated in the 14 coastal provinces of PNG. Cocoa plantings occupy approximately 27% of the total area of 476,000 ha under export tree crops. Approximately 80% of the crop is produced by smallholders and this proportion is likely to increase.

Despite the healthy market demand for cocoa, smallholder yields in PNG have generally been far lower than those potentially attainable, and recently they have fallen even further due to widening infestations of cocoa pod borer. For the cocoa industry to recover and prosper, it is essential that management of smallholder cocoa blocks improves dramatically. Many aspects of good management, such as pest control, are fairly well understood, and the Australian Centre for International Agricultural Research (ACIAR) has been involved in partnerships with PNG organisations to carry out some of the necessary research. However, there is little information on appropriate nutrient management for cocoa in PNG. Therefore, ACIAR supported this study to identify possible nutrition-related constraints on productivity and recommend what steps should be taken next. I hope that the results of this detailed, nationwide study will lead to increased productivity of this important tree crop.

Nick Austin
Chief Executive Officer
ACIAR

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Abbreviations

Al	aluminium
B	boron
C	carbon
Ca	calcium
$CaCl_2$	calcium chloride
CCI	Cocoa Coconut Institute, Papua New Guinea
CEC	cation exchange capacity
Co	cobalt
$cmol_c$	centimoles of charge
CSIRO	Commonwealth Scientific and Industrial Research Organisation, Australia
Cu	copper
DTPA	diethylene triamine penta-acetic acid
EC	electrical conductivity
Fe	iron
ha	hectare
IPDM	integrated pest and disease management
K	potassium
KCl	potassium chloride
kg	kilogram
M	molar
Mg	magnesium
mg	milligram
Mn	manganese
N	nitrogen
$NaHCO_3$	sodium bicarbonate
NARI	National Agricultural Research Institute, Papua New Guinea
Ni	nickel
P	phosphorus
PBI	phosphate buffer index
PGK	Papua New Guinea kina
PNG	Papua New Guinea
PNGRIS	Papua New Guinea Resource Information System
PSI	phosphate sorption index
S	sulfur
t	tonne
Ti	titanium
VSD	vascular streak disease
XRD	X-ray diffraction
XRF	X-ray fluorescence
Zn	zinc

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Summary

Cocoa is grown by approximately 151,000 households in Papua New Guinea (PNG). Smallholders, who produce 80% of the crop, have annual yields far below the potential of 4.4 tonnes/hectare. Yields are low for many socioeconomic and agronomic reasons. The aim of this study was to determine the nutrient status of cocoa grown in PNG, and to recommend further steps to determine if there are nutrient-related constraints on productivity and how they might be overcome.

Leaf and soil nutrient contents were measured and grower practices were recorded at 63 cocoa blocks (smallholders, on plantations or on research stations) across the country. A wide variety of plant species were present in blocks, with *Gliricidia* being the most common shade tree. Based on published 'critical' levels for cocoa leaf nutrient contents, nitrogen and iron deficiencies occurred in more than 89% of the blocks and phosphorus deficiencies in about 25%. Leaf magnesium concentrations were mostly adequate, except in East New Britain, where 64% of the blocks were deficient. Deficiencies of potassium, calcium, manganese, boron, copper and zinc were encountered in 2–15% of the blocks. However, the 'critical' levels must be regarded with caution, as the micronutrient (manganese, boron, copper, iron and zinc) values were based on surveys rather than manipulative experiments, and the macronutrient (nitrogen, phosphorus, potassium, magnesium and calcium) values were established in different places with different planting materials. Leaf potassium and phosphorus contents were related to soil type and nutrient contents. In blocks that are being well maintained and regularly harvested, it is likely that yield is being constrained by nutrient deficiencies.

Management of cocoa blocks in PNG must improve dramatically for the cocoa industry to prosper, and perhaps even to survive, particularly with the recent spread of cocoa pod borer, which is drastically reducing cocoa yields. To improve management and yields, the industry requires reliable critical levels of leaf nutrient concentrations, and nutrient management recommendations appropriate to different regions, based on trials. Effective means of facilitating adoption of improved practices must also be developed.

Background and aims

Cocoa (*Theobroma cacao*) is one of the most economically important cash crops in PNG. It is the primary cash crop in most coastal areas of PNG, being grown on an estimated 100,000–130,000 hectares (ha) by around 151,000 smallholders or 16% of the households in the country. Just over one million people in PNG depend on cocoa for their livelihood (Omuru et al. 2001).

In 2009, exported cocoa was estimated at 51,000 tonnes (t), bringing in annual export earnings of around PGK331 million. However, the industry is threatened by cocoa pod borer (*Conopomorpha cramerella*). Until 2008, the Gazelle Peninsula of East New Britain province was the most important cocoa-growing region, producing about 20,000 t or 54% of national production. In 2009, annual production from East New Britain fell by over 60% to approximately 8,000 t (C.S. Parik, economist, Cocoa Board, pers. comm.) because of losses to cocoa pod borer. This loss in production was offset by increased production from the Autonomous Region of Bougainville and East Sepik province. Cocoa pod borer is present in both these provinces and in Madang province, and poses the most serious challenge to the industry in the coming years.

Plantation production of cocoa has been declining since the mid 1970s mainly because of rising production costs and the closure of the Bougainville plantations in 1988–89 with the outbreak of civil war in that province. In contrast, smallholder production has been on the rise from about 6,800 t in 1972–73 to its present level of approximately 40,000 t.

Despite the importance of cocoa to the economy, the industry is plagued by poor management practices that result in low yields. Most PNG smallholder cocoa is currently produced using a 'foraging' production strategy with virtually no management inputs. Yields are very low, generally in the range 0.3–0.4 t/ha of dry bean annually. Yield potential is much higher, with yields of up to 4.4 t/ha observed in research trials, and between 1.5 t/ha and 2.5 t/ha obtained in plantations.

Given the size of the smallholder contribution to the industry, it is clear that even a small increase in smallholder productivity could have a substantial effect on export income and increase growers' cash income. For the industry to survive and prosper, management inputs to smallholder cocoa blocks must improve substantially. This is particularly important with the recent spread of cocoa pod borer, because the pest can devastate crops unless levels of management are high. Good nutrient management is an important part of the picture; however, there is little information on nutrient management to guide PNG cocoa growers. Even if nutrient management were improved, no lift in productivity would be expected without improved management of cocoa and shade trees, pests and diseases, weeds and harvesting.

The purpose of this study was to determine the nutrient status of cocoa trees and cocoa-growing soils throughout the key growing areas of the country. The information is intended to help assess whether or not productivity is constrained by nutrition and related factors, to help design future research activities that address possible constraints, to provide recommendations to overcome possible nutrition-related constraints on productivity and to implement solutions.

Constraints on cocoa productivity in PNG

For some time a number of limitations to cocoa productivity have been known; there have been attempts to overcome them, but there have been no long-lasting solutions. These factors are discussed below, drawing on the studies of Curry et al. (2007) and references therein. Most of these studies were in East New Britain province, but the general conclusions were confirmed in our study. Common factors explaining low productivity are land shortages, relatively low cocoa prices, labour shortages, low levels of block maintenance and lack of appropriate agronomic knowledge. In addition, growers report theft as a major limitation to productivity. Finally, Curry et al. (2007) noted that accessibility of healthy, ripe pods is of critical importance.

Nutrition has not been reported as a constraint in previous studies. However, nutrition-related factors, such as 'lack of fertiliser' were raised as a limitation to yield by several smallholders in our survey of growers.

There are no external market constraints to increasing the productivity from cocoa blocks. World demand for cocoa is increasing rapidly and there will be a high demand for PNG cocoa into the foreseeable future, even if production were much higher. PNG cocoa is known for its good and consistent quality, with particular flavour, high fat content and large beans (Smilja Lambert, Mars, Incorporated, pers. comm.) and, in early 2008, PNG had its 'fine flavour status' reinstated, which adds a premium to the world market price. PNG's fine flavour status is probably due mainly to two factors: good germplasm and good quality control, including organisation of the fermentation and drying of cocoa beans. The main threat to the fine flavour status of PNG cocoa is smoke taints introduced during the drying process. So, while quality and demand are good, productivity is the main limitation to increased income from cocoa.

Smallholder production strategies

Cocoa producers have a variety of cash income sources, including copra, garden food (sold at local markets), betel nut, vanilla, livestock and trade stores. For women, income from local markets is ranked the most important.

Cocoa producers sell either dry bean or wet bean, which is related to various factors such as the age of their cocoa trees, yields, block condition and access to processing facilities. Most cocoa producers in East New Britain province, and probably throughout PNG, are wet bean sellers. They derive most of their income from local markets, copra and other sources for most of the year, and therefore spend less effort on cocoa production. Wet bean sellers tend to harvest older stands characterised by higher levels of pests and diseases, unpruned cocoa trees and dense shade due to lack of pruning. The cash they earn from cocoa is spent on small items or immediate needs. Income from cocoa is far higher for dry bean sellers than wet bean sellers. Dry bean sellers are more narrowly focused on cocoa production and derive most of their income from cocoa. They depend on a ready supply of labour, access to a fermentary and drier, and transport for firewood and for bringing processed crop to exporters.

Cocoa production peaks when the trees are between 3 and 7 years old, and then falls off. The decline in productivity appears to be particularly rapid with hybrids and clones planted since the 1980s. With the Trinitario variety of cocoa planted pre-1980, productivity tended to last longer, with lower levels of management.

Land shortages and land tenure

Land shortages are common in the main growing areas, such as the Gazelle Peninsula, and are reflected in the relatively high proportion of cocoa being planted on land that has been removed from customary tenure and therefore not subject to ownership claims by the broader customary landowning group (Curry et al. 2007). There is a desire among many smallholders, especially in East New Britain province, to convert customary tenure of cocoa blocks to more individualised forms of land tenure, due to capital and labour investments in the block, and the desire to give sons in this matrilineal society primary inheritance rights. Protracted disputes over inheritance often limit the incentive to provide labour inputs. Also, in many parts of PNG, land is often planted to perennial cash crops as a way to lock it up to meet the future livelihood needs of the family. Cocoa blocks planted for this reason could be expected to have low maintenance levels, but low levels of maintenance are common across all tenure types.

Cocoa price

PNG farmers are price-sensitive, which affects their behaviour in several ways, but tends to mean that production levels and block maintenance levels are high when the price is high. In May 2010, growers were obtaining about PGK450/bag (62.5 kg) of dry bean, at a world market price of US$3,094/t. About PGK40/t is paid in levies. Transport is a high proportion of the cost of production, especially for dry bean producers. The break-even yield is about 0.7 t/ha for plantations and about 0.3 t/ha for smallholders.

Labour management and shortages

Labour shortages are a significant constraint on productivity. Cocoa growers rely on unpaid labour from the extended family, and there are many reasons why there may not be enough labour on particular blocks at the right times. Activities that are not related to cash income, but are central to maintaining social cohesiveness and kinship networks, tend to draw a lot of time and labour away from cocoa production. However, these obligations may also have the opposite effect—motivating smallholders to commit extra time and labour to raise funds for social purposes. The availability of labour is not simply demographic, but depends on a wide range of factors.

Households with an adequate supply of labour have certain characteristics. Typically they:

- reside in multigenerational extended family units with houses clustered together
- work (subsistence and cash cropping) as large groups made up of multihousehold units
- have access to the labour of their sons
- do not or rarely have intra-household disputes over labour allocation and the distribution of household income
- use indigenous mechanisms of labour mobilisation when necessary to maintain cocoa production during high crop periods.

In addition, the head of the household:

- maintains control over family labour, especially adult sons
- allocates cocoa harvests or beans to adult household members and other relatives.

Harmonious relationships within and between families are critical for ensuring ongoing labour commitment, which is very important for meeting peak labour demands during flush periods. Individuals must be satisfied that the income sharing is fair. By judiciously allocating harvest rounds to co-resident adult sons, the household head builds goodwill, allowing him to draw on their unpaid labour. Traditional methods of ensuring long-term supply of labour include adoption or recruitment of relatives to reside with the household. More common methods are shorter term and rely on gift exchange. Cash and food may be given as tokens of appreciation for the gift of labour, and are usually not interpreted as market payments of labour as occurs under wage labour arrangements.

Constraints on the availability of labour may be short term or long term. Households with labour constraints tend to have:

- few adults or older children
- health problems
- competing demands on labour (e.g. paid work, other cash crops)
- non-economic competing activities (e.g. customary and church activities)
- underused available labour (e.g. due to inadequate remuneration)
- the perception that the household head is not fulfilling his obligations to the family
- minimal use of traditional strategies for labour mobilisation or of hired labour.

Dry bean sellers are more reliant on a ready supply of labour than wet bean sellers. They require a mean of 4.4 harvesters for 2.3 days per sale, compared with wet bean sellers who require a mean of 1.8 harvesters for 0.4 days per sale (Curry et al. 2007). Wet bean sellers harvest smaller quantities, more often, and are less dependent on labour from the extended family. They are typically women working alone or with children, or elderly men.

Men, who are more involved in dry bean processing, tend to spend more time and derive more income from cocoa than women.

Block maintenance

Block condition is very poor on most blocks, especially on blocks older than 8–9 years. Access for harvesting can be difficult because of the dense vegetation structure. Low levels of maintenance lead to low accessibility of healthy, ripe pods, and a downward spiral of productivity in which incentives to invest labour in block maintenance decline further as returns to labour decline. On most smallholder blocks there is virtually no pruning of cocoa, little or no shade control, no pest or disease control measures, and high rates of underharvesting, leading to low yields and a high incidence of black pod disease. Weed control is generally adequate only in younger, higher producing blocks during flush periods. Weeding is mostly carried out for harvest access rather than for sanitation or tree health. Pruning, shade control and weeding are done mostly to promote the growth of food crops intercropped with cocoa during the first few years of the block. After 2–3 years, these activities are minimal.

There is widespread recognition of losses due to black pod, canker and vascular streak disease (VSD). Black pod and canker are caused by *Phytophthora palmivora*, which has a complex disease cycle. High levels of disease are related to poor block maintenance and underharvesting. Curry et al. (2007) found significant underharvesting, especially in older, bigger trees, with 29% of full-size pods being dry (i.e. not harvested when ripe). VSD, caused by *Oncobasidium theobromae*, is a systemic pathogen that is absent in the Autonomous Region of Bougainville, and in New Ireland and Manus provinces. Pink disease, caused by *Corticium salmonicolor*, is another disease of concern in Bougainville and in Northern Province, as it possibly reduces productivity. Poor block maintenance has been an intractable problem in cocoa productivity, despite much extension effort. Additionally, lack of knowledge and lack of appropriate tools are factors limiting productivity. Farmers often express a desire for more training. Inadequate tools result in damage to flower cushions during harvesting and inadequate pruning and weed control.

Accessibility of healthy, ripe pods

The accessibility of healthy, ripe pods is of critical importance for productivity. Low accessibility is a major disincentive for harvesting, and there is a minimum threshold below which labour inputs become minimal and limited to the extent of 'forage' harvesting. The quantity threshold parallels labour strategies in subsistence gardening; in old food gardens nutrients are depleted and weeds build up, and less effort is spent on weeding and general garden maintenance. Instead, the garden is allowed to revert to fallow with forage harvesting of residual food crops. In other words, a farming strategy is replaced with a foraging strategy of production.

Theft is rated by growers as a major constraint on productivity and greatly reduces their motivation to harvest and invest labour in their blocks. While there have been no studies on the importance of theft, it is likely that the most easily accessible pods are stolen (the low hanging fruit), leaving the less accessible pods (e.g. pods higher in the tree). The reduction in the quantity of healthy, ripe pods that are easily accessible reduces the blockholder's motivation to harvest, in the same way that an older cocoa block with dense vegetation and high pest and disease levels makes harvesting more difficult.

Synthesis of constraints into a smallholder cocoa production model

Curry et al. (2007) proposed a model that explains typical cocoa production strategies and constraints on productivity. In the model, management of cocoa blocks proceeds in three stages, in which tree age is a major factor. As the trees age, yields and management inputs deteriorate.

In stage I (< 3 years old), the cocoa is immature, productivity is low and the incidence of pests and diseases is low. Labour inputs are moderate, but the block is well maintained, mostly because of efforts being applied to intercropped food gardens. Any cocoa harvested is sold as wet bean due to the low yields.

In stage II (3–8 years old), the cocoa is mature, the vegetation structure is open and there are large quantities of ripe pods accessible, leading to high labour inputs and high productivity. This is the period in which cocoa may be sold as dry bean, leading to high income. Although income is good in stage II, it is generally not invested in block maintenance. The incidence of pests and diseases rises during this stage.

In stage III (7–8+ years old), the cocoa is senile and accessibility of ripe pods is low due to taller, denser vegetation and a high rate of diseased pods. Labour inputs and productivity are low, cocoa is mostly sold as wet bean and there are lower returns to labour. Lack of pruning and shade control, together with no pest and disease management, make the transition from stage II to III inevitable for most smallholders.

Raising smallholder productivity is very difficult due to the complexity of the situation. Many years of extension and training have not generated significant improvements in block management or productivity. Strategies currently being proposed for delaying the transition into stage III must be innovative; must accommodate existing practices, extension efforts, and smallholder needs and circumstances; and must create better incentives for devoting more time and labour to cocoa.

David Yinil (Senior Agronomist, Cocoa Coconut Institute) discussing constraints on cocoa productivity with growers and researchers in East New Britain province (Photo: John Armour)

Previous cocoa nutrition research in PNG

Low yields can be attributed to many factors, but at least part of the reason appears to be nutrient deficiencies. Many existing cocoa farms in PNG have been growing cocoa for 15 years or more, with little or no addition of fertiliser. These farms may have also undergone new plantings and rehabilitation, also with little or no addition of fertiliser. In addition, it has been observed that young cocoa develops better in completely new plantings than when replanted in existing cocoa stands, suggesting that adequate nutrition is an important factor in cocoa development. Furthermore, it is estimated that 1,000 kg of dry cocoa beans can remove, through cocoa beans and pod husks, 31–40 kg nitrogen (N), 5–6 kg phosphorus (P), 54–86 kg potassium (K), 5–8 kg calcium (Ca) and 5–7 kg magnesium (Mg) (Wessel 1985). Based on these figures, over 15 years, an average annual yield of 0.4 t/ha of dry cocoa beans (commonly obtained from many smallholder farms in PNG) would have removed from one hectare 216 kg N, 36 kg P, 432 kg K, 42 kg Ca, and 36 kg Mg. These losses may lead to a deficiency in one or more nutrient elements, thus limiting growth, development, maximum yield potential and sustained production of cocoa. Finally, in some areas where cocoa is grown, soils are known to have low plant-available supplies of some elements (e.g. K in coralline soils).

The current yield decline in hybrids after reaching maximum production between 5 and 7 years after planting could be strongly linked to nutritional problems. Research data from a shade × spacing × clone experiment on volcanic ash soils at the Cocoa Coconut Institute (CCI), Tavilo, showed that even when no fertiliser was used, a hybrid cocoa clone can yield over 2.0 t/ha of dry beans per year when shade was removed. However, the 2002 soil analysis data in this experiment showed declining levels of Ca, K, Mg, P, cation exchange capacity (CEC), organic carbon (C) and N, raising concerns about the long-term sustainability of these yields. The decline in soil nutrients should be a major concern, particularly when over 80% of the cocoa exported from PNG is produced on these volcanic ash soils in East New Britain province and the Autonomous Region of Bougainville, with little or no fertiliser additions. The problem could be very serious on the non-volcanic soils, especially coralline clay soils where K has been found to be highly deficient.

Early cocoa fertiliser trial work in PNG has been reviewed by Byrne (1971), Charles (1971) and Powell (1991). Other cocoa fertiliser trials in Northern Province were reported by Wallace (1991). Trinitario seed cocoa generally responded best to fertilisers under conditions of little or no shade (Powell 1991). Based on those trials, quarterly applications of N (100 g/tree/application being the optimum rate) were recommended (Ling 1989). Further trials by the Department of Agriculture and Livestock occurred in the 1980s, but had many problems, including plots that were too small and a lack of understanding of the phenological cycle of the crop. There is little or no documentation of those trials. Ling (1989) reported that there was no significant response to N fertiliser in the first 2 years of application in hybrid cocoa. The CCI also did some work on fertilisers in the 1990s, but the trials were discontinued as a result of inappropriate experimental procedures and loss of data and information; no recommendations were made. There are recommendations for fertiliser use in hybrid cocoa in a cocoa and coconut manual for PNG, but these appear to be based on observations and common understanding, with little scientific basis. There is currently a fertiliser trial at Tavilo that is related to cocoa rehabilitation with and without the use of fertilisers. Responses to fertiliser were evident in the first 18 months.

Although fertiliser is generally not used by smallholders, it is applied in some plantations. Newmark applies fertiliser in all their plantations in East New Britain province at an annual rate of approximately 60 g N, 14 g P, 20 g K and 9 g Mg per tree, as well as 100 g urea in September, 120 g NPKMg 12:12:17:2 in April and 40–50 g kieserite in April (G. McNally, Newmark Plantations, pers. comm.).

The role of nutrition in relation to tree health and yield decline of the present cocoa planting material is not fully understood. It is highly likely that nutrient management, depending on the agroecological environments and other agronomic practices (such as weed control, shade control, type of shade tree used, cocoa pruning and control of pests and diseases) could be one of the major links to tree health, bearing capacity and yield decline.

For biophysical limitations to production to be overcome, it is essential that agronomic factors be assessed together with socioeconomic factors. This is particularly important in PNG, where income generation from cash crops is often less important than other social imperatives. A 2002 study (Australian Centre for International Agricultural Research, ASEM/2002/014) found that cocoa management strategies change markedly over time. In the first few productive years of a cocoa block the crop is managed as an agricultural crop, whereas in later years it is exploited more like a resource to be gathered when some cash is required. Fertiliser is not currently used by most smallholder cocoa growers, and there are many socioeconomic reasons that are likely to limit uptake of new nutrient management technologies. Marrying biophysical and socioeconomic aspects of nutrient management is of critical importance in designing future research projects and planning investments in research and development. Results from such research will allow for more-effective investment into alleviating poverty and improving livelihoods of growers in the PNG coastal lowlands.

Clearly, there is a general lack of data on:

- current soil fertility and crop nutrition status
- pest and disease incidence
- crop productivity on smallholder blocks.

There is also a lack of systematic knowledge of what growers are already doing or what their attitude to a range of soil management options may be.

Leaf symptoms of potassium deficiency in cocoa grown on a coralline soil in East New Britain province (Photo: Paul Nelson)

Study methods

The study involved two workshops, a survey of cocoa growers across the country who were asked about management practices, and the analysis of soil and plant tissue samples.

Workshops

The first workshop was held in March 2007 at Tavilo, East New Britain. It involved 35 participants including cocoa growers from the local Tokiala community, and staff from research and government institutions (CCI, National Agricultural Research Institute [NARI], PNG Department of Agriculture and Livestock, PNG Department of Primary Industry, PNG Oil Palm Research Association, Commonwealth Scientific and Industrial Research Organisation (CSIRO), Queensland Department of Natural Resources and Water, James Cook University and Curtin University of Technology), industry organisations (Kokonas Industri Koporesen) and plantation companies (Newmark Plantations). Existing information on cocoa nutrition and related issues were reviewed, needs for research were discussed and the cocoa block survey was designed, including the selection of sites and the development of sampling protocols. The sampling protocols were field tested on two smallholder blocks at Tokiala, and an integrated pest and disease management (IPDM) trial block. Using available resources, such as the PNG Resource Information System (PNGRIS), Hanson et al. (1998) and local knowledge, a working group selected the most appropriate sites to sample. The sites were intended to cover the main areas of current or potential cocoa production. The sites were classified as 'main areas', which are already important cocoa growing areas, and 'other areas', which are less important in terms of cocoa production or are potential areas of cocoa production. Shortly after the workshop, several CCI staff were trained in the techniques needed for tissue and soil sampling, and the survey and sampling protocols were refined. The training included concepts to avoid contamination between samples, subsampling, practical techniques to minimise chances of mislabelling samples, use of the global positioning system, organisation of data, organisation of staff and interviewing the landowner.

The second workshop was held in March 2008, also at Tavilo, East New Britain. There were 52 participants: 45 from PNG and 7 from Australia. Participants included cocoa farmers and staff from research institutions (CCI, Coffee Research Institute, PNG Oil Palm Research Association, CSIRO, Queensland Department of Natural Resources and Water), universities (James Cook University, Curtin University of Technology, University of Natural Resources and Environment, formerly Vudal University), industry organisations (Cocoa Board, Coffee Industry Corporation), plantation companies (Newmark, Ramu), consultants (One Stop Cocoa) and companies involved in buying or processing cocoa (Mars). The aim of the workshop was to:

- review the results of the plant and soil analysis from the 63 sites sampled to assess the nutritional status of cocoa in PNG
- solicit ideas, based on the results of this project, for a potential future project on cocoa nutrition.

To benefit from other nutrition work in PNG, researchers from the oil palm, coffee and sugarcane industries were also invited to participate. Similar to the first workshop, there were reviews as well as small working-group discussions.

Survey and collection of soil and tissue samples

Between April and November 2007, 63 sites in nine provinces were sampled, and the grower at each site was surveyed. The final selection of sites and the number of sites sampled in each province depended to some extent on the practical aspects of travel, time available in the province and the weather during travel.

Of the 63 sites surveyed, 48 were on smallholder blocks, 6 were on plantations, 8 were in CCI trials and 1 (site 62) was on a potential cocoa site

(Table A1). By province, 11 sites were in East New Britain, 9 in the Autonomous Region of Bougainville, 9 in New Ireland, 8 in Madang, 8 in East Sepik, 6 in Morobe, 6 in Northern, 4 in West Sepik and 2 in the Jimi Valley of Western Highlands. Site locations are shown in Figure 1.

Once a site had been selected, a block of 42 (6 × 7) trees was selected for sampling. The plot was assessed for tree health and general maintenance. The grower was asked questions about this particular part of the block and also about their whole block. An attempt was made to calculate yield at each site from information supplied by the grower, but it was not possible to make reliable estimates.

Leaves were sampled at every site (except for site 62, which is a potential cocoa site with no cocoa planted) from 20 trees distributed evenly throughout the 42-tree block. The leaves sampled (2 per tree) were the third leaf of a recently hardened leaf flush at mid-canopy height. These specifications were used to standardise, as closely as possible, the age and light exposure of the leaves, both of which affect nutrient content (Wessel 1985). The number of leaves on the sampled flush was recorded, and their length, width and fresh weight were measured. Leaves were dried as rapidly as possible under fans, air conditioners or in an oven set at 65 °C. Eventually, all leaves were dried in an oven set at 65 °C, weighed and ground, and a composite sample was prepared for each site.

Pods were sampled from eight sites in the following provinces: sites 4 and 63 in East New Britain, site 8 in Bougainville, sites 18 and 25 in New Ireland, site 34 in Morobe, site 35 in Northern and site 44 in Madang. At each site, 10 ripe pods were picked, with no more than one pod picked per tree. The beans and husks were separated, weighed, dried and weighed again. They were then ground and mixed, and a composite subsample of husk and beans was prepared for each site.

Soil samples were taken at every site (except for site 19) at depths of 0–0.15 m, 0.15–0.30 m, 0.3–0.6 m and 0.6–0.9 m, using an auger. Samples were taken 1 m from the tree trunk at trees distributed evenly throughout the 42-tree block. The shallowest depth increments were sampled at nine trees and the deeper increments at five of those trees. Soil was broken up through a 10 mm sieve, and one composite sample was prepared for each depth increment at each site. It was initially intended to dig a pit at every site and take undisturbed cores for a bulk density measurement, but that process proved too time-consuming for the limitations of the project and was abandoned.

At CCI Tavilo (SG2 hybrid seed garden), leaf samples were taken from several clones used as parents of released hybrids (Efron 2003).

Data for each site was recorded on a survey form. Samples were processed (plant tissue samples dried and ground, soil samples kept at field moisture) on site and shipped to Australia for analysis, with a duplicate sample transported to CCI at Tavilo, East New Britain, as a backup. On return to CCI, photocopies of the survey sheets were sent to Australia as a backup.

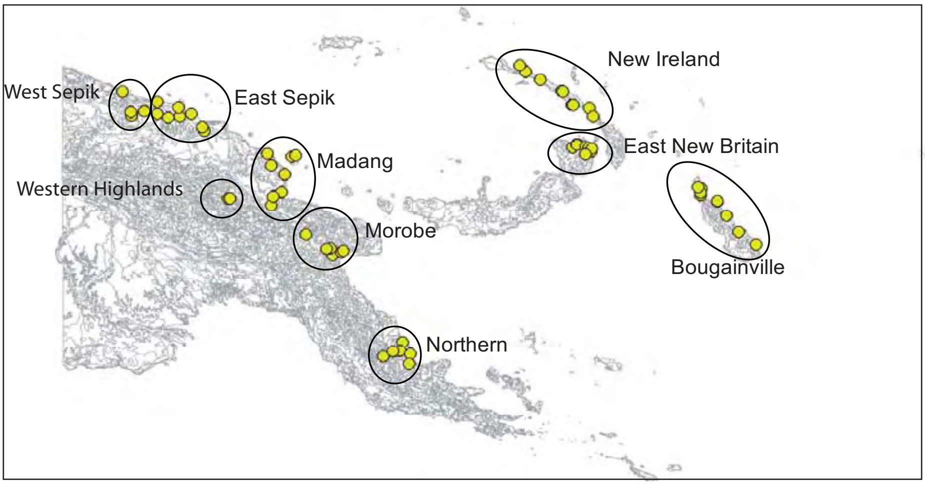


Figure 1. Location, by province, of cocoa sites surveyed and sampled

Analysis of plant and soil samples

Plant tissue samples were subjected to Australian Quarantine and Inspection Service-approved treatment (85 °C, 8 hours) and then released from quarantine at CSIRO, Townsville. They were analysed for N by combustion (Matejovic 1996) using an Elementar instrument, and for P, K, Ca, Mg, sulfur (S), iron (Fe), manganese (Mn), zinc (Zn), copper (Cu), boron (B), nickel (Ni), cobalt (Co), aluminium (Al) and titanium (Ti) by inductively coupled plasma optical emission spectrometry following digestion in nitric acid (Zarcinas et al. 1987). Waite Analytical Services, Adelaide, analysed all the plant samples.

Soil samples were analysed in an Australian Quarantine and Inspection Service-approved laboratory at CSIRO, Townsville, mostly using methods described by Rayment and Higginson (1992) that are subsequently referred to by the method number used in that publication. Samples from all sites and all depths were analysed for water content, field texture, electrical conductivity (EC) of a 1:5 soil:water extract (method 3A1) followed by pH_{water} (method 4A11; 1:5 soil:water, 1-hour shake) and pH_{CaCl2} (method 4B21; addition of $CaCl_2$ to bring solution concentration to 0.01 M $CaCl_2$) in the same extract, CEC, anion exchange capacity and exchangeable cations (Gillman and Sumpter 1986), 'Colwell' extractable P (method 9B11; 1:100 soil:solution, 16-hour shake with 0.5 M $NaHCO_3$ at pH 8.5, manual colorimetric determination after acid neutralisation step), extractable Al (1 M KCl extractant, read colorimetrically using the pyrocatechol-violet method, modified from the method of Dougan and Wilson 1974), organic C (Heanes 1984 and method 6B11) and total N (method 7A11; Kjeldahl digest, read colorimetrically using a segmented flow autoanalyser).

Soil P was measured using the Colwell method rather than other methods previously used in the cocoa industry because it reflects the 'quantity' component of the labile pool of soil P, thus providing an estimate of P fertility that is more relevant for a long-term tree crop such as cocoa. Much of the existing soil P data from PNG has been obtained using the method of Olsen et al. (1954), which has a

Peter Bapiwai (Cocoa Coconut Institute) interviewing a cocoa grower in East New Britain province (Photo: Paul Nelson) short extraction time and narrow soil:solution ratio compared to the Colwell method, and is expected to reflect 'intensity' rather than 'quantity'. Samples with $pH_{water} > 6.5$ were analysed for carbonate as $CaCO_3$ equivalent (method 19A11). Samples from the 0–0.15 m depth (all sites) were analysed for their phosphate buffer index (PBI; Burkitt et al. 2002) and phosphate sorption index (PSI; method 9I11), and for diethylene triamine penta-acetic acid (DTPA)-extractable Zn, Cu, Mn and Fe (method 12A11). Samples from 0.3–0.6 m depth (all sites) were analysed for pH_{NaF} as a surrogate for allophane content, as suggested by Fielders and Perrott (1966) (method 4D11).

Soil samples from 20 sites, selected to cover the range of soil types, were analysed for mineralogical parameters (0.3–0.6 m depth). The mineralogical parameters were pyrophosphate-extractable Al (method 13B11) and oxalate-extractable Al and Si (method 13A11), used to calculate allophane content (Parfitt and Childs 1988), total elemental analysis by X-ray fluorescence (XRF) and mineral-layer spacings by X-ray diffraction (XRD). For the XRF analyses, samples were fused with lithium borate and analysed on a Philips PW1480 wavelength dispersive XRF system. For XRD analysis, the samples were examined as powders. XRD patterns were recorded with a Philips PW1800 diffractometer.

A selection of soil samples were to be analysed for a selected range of parameters at the NARI chemistry laboratory for comparison, but the laboratory was not operating during the period of this project.

Characteristics of surveyed sites

Most of the sites were on flat to moderately sloping land with reasonably deep soil (neither an impeding layer such as rock nor the watertable reached within 0.9 m depth). However, there were sites, particularly in Northern Province, that had a shallow depth of soil before rock was reached. Where erosion was observed, it was often attributed to poor groundcover or to steeper slopes.

Block tenure, planting history and vegetation

The cocoa blocks surveyed covered a range of tenure types, age and other characteristics (Table A2). Most of the smallholder blocks were on customary land (73%), with some on purchased land (23%) or state land (4%). Most of the blocks had been farmed for more than 17 years (85%) and most of the current cocoa stands were more than 7 years old (86%). The dates of clearing and cocoa plantings are shown in Table 1. Most of the planting materials were sourced from CCI, with the type of material corresponding to planting date: Trinitario open-pollinated material before 1982, generation 1 (SG1) hybrids from 1982 to 1986, generation 2 (SG2) hybrids from 1986 to 1994, and clones from then on. However, some plantings made since 1982 (five blocks) used Trinitario material sourced from older blocks or neighbours. Of the 63 growers interviewed, 60 were male.

Smallholder cocoa blocks had a larger variety of plant species than the CCI or plantation blocks. Most of the blocks had, as shade trees, *Gliricidia* (58% of blocks), coconuts (48% of blocks) or both. Many blocks had other shade trees, including betel nut, banana, breadfruit, galip or leucaena. Food crops were common among the cocoa, especially in younger plantings; 45% of smallholder blocks had food crops and 73% had fruit or nut trees among the shade trees, whereas the corresponding figures were 0% and 12% on CCI or plantation blocks. Many of the smallholder blocks had *Gliricidia* as a shade tree in the sampled plots (57%), and a small proportion (21%) had legumes in the groundcover, mostly *Pueraria*. The corresponding figures were similar on CCI and plantation blocks.

Block management and constraints on yield (other than nutrition)

It was clear from the survey that smallholder growers considered lack of knowledge, poor management and availability of labour to be the main factors constraining productivity. Of the smallholders interviewed, 13 were happy with their yields and 44 were not. Forty-five of the smallholders gave reasons for why their yields were good or not. The reasons given for good yields were adequate labour, good market access, absence of land disputes, good planting material, good knowledge or experience due to training or experience in plantation management, and good management, including IPDM technology (Table 2, Table A3). The reasons given for poor yields revolved mostly around poor knowledge and poor management, labour shortages and disputes, competing demands on growers' time, old planting materials or lack of finance for replanting blocks (Table 2, Table A3). Lack of fertiliser application and poor soil fertility were cited 15 times, which is interesting as previous surveys have not recorded that

Table 1. History of cocoa blocks (% of responses)

Block history	Before 1970	1970–79	1980–89	1990–99	2000–07
Block first farmed	41	13	30	11	4
Cocoa first planted	13	16	33	24	13
Current stand planted		4	24	48	24

concern. However, this survey was possibly biased because the interviewers explained to the growers that the soil and tissue sampling exercise was intended to assess fertility and nutrient status of the soil and plants. Several growers asked about specific management issues (e.g. How should I prune my cocoa? How should I rehabilitate my cocoa? How should I control pests and diseases?), reflecting the general lack of confidence in their ability to manage cocoa well. Several asked about their soil (e.g. Could there be an issue with fertility?). One grower had taken over a block to which fertiliser had been applied in the past.

Table 2. Reasons cited by smallholders for good or poor cocoa yields

Reasons for good yield	Response	Reasons for poor yield	Response
Labour adequate	5	Knowledge lacking	22
Access good	5	Management poor	18
Land tenure secure: no disputes	4	Labour shortage/dispute/cost/other commitments	17
Planting material good (new)	3	Planting material old (Trinitario)	11
Knowledge/experience good	3	Diseases and pests	10
Management good	2	Fertiliser lacking	10
		Finance for purchasing seedlings or tools lacking	6
		Nutrient deficiency / soil exhaustion	5
		Theft of pods	4
		Limited access to functioning fermentary or dryer	4
		Waterlogging or flooding	3
		Price low	3
		Other chemicals (not fertiliser) lacking	2
		Support by government lacking	3
		Land shortage	1
		Bad weather destroying flowers	1
		Access poor	1
		Missing trees	1

Buan Levita's cocoa block (site 13) in Teabes village, Autonomous Region of Bougainville. The cocoa in this block is unshaded, although *Gliricidia* cuttings have been planted recently. *Pueraria* is grown as a cover crop. The current stand was planted in 2000. (Photo: Chris Fidelis)

He wondered if the application of inorganic fertilisers could be affecting his production and if the fertilisers could be detected in the soil tests. Many smallholders felt a lack of support and several wanted to know how this exercise would benefit them.

Of the management factors assessed, pruning received the worst ratings, with 48% of blocks scored as poor or very poor. Shade management was also rated poorly (42% poor or very poor) while weed management scored the best (27% poor or very poor). In many cases the good score for weed management was at least partly related to the canopy being so dense (due to poor or no pruning of cocoa and shade trees) that there was not enough light for weeds to grow well. The distribution of management ratings is shown in Table 3 and in more detail in Table A4.

Of the diseases assessed, black pod was the most widespread and severe, with 98% of blocks affected. Next came canker (91% of blocks affected), pink disease (62% of blocks affected) and VSD (55% of blocks affected). The severity of the diseases is shown in Table 4 and Table A4. Thread blight was noted in many blocks.

Table 3. Rating scores for management of cocoa blocks (% of smallholder blocks)

Management practice	Very poor	Poor	Average	Good	Very good
Tree health	0	16	30	52	2
Shade management	9	33	41	15	2
Weed management	8	19	42	29	2
Pruning	15	33	35	17	0

Table 4. Rating scores for diseases in cocoa blocks (% of smallholder blocks)

Disease	Severe	Moderate	Low	None
Black pod	8	33	56	2
Canker	2	13	77	9
Vascular streak disease	0	9	47	45
Pink disease	0	15	48	38

Clement Bori in his cocoa block (site 53) in Wani village, East Sepik province. He uses leucaena and betel nut as shade trees and has planted intercrops such as bananas. The cocoa, which was planted in 1974, receives low management inputs. (Photo: Chris Fidelis)

Approximately one-third of growers had applied fertiliser (29% of smallholders and 33% of CCI or plantation blocks). The smallholders who had applied fertiliser were mostly participating in the IPDM trials, and it was only to that part of their block (option 4) that they had applied fertiliser. The survey sought out IPDM blocks for sampling, so the high proportion of smallholders who had applied fertiliser was not representative of the industry as a whole. However, there were a few smallholders who had applied fertiliser at some time to part of their block of their own initiative. The IPDM farmers used urea and NPK. The other smallholders who had used fertilisers had mostly used NPK, but one had used urea and chicken manure. The plantations had mostly used urea and NPK, but some had used muriate of potash and sulfate of ammonia. Almost all the growers who had used fertilisers reported improvements in vegetative growth, flowering and pod production, but there were concerns about the cost (Table 5). One grower thought fertiliser should not be used because development of the industry depended on organic cocoa and because fertiliser is too expensive.

Table 5. Comments on the effects of fertilisers (mostly NPK and/or urea) by cocoa growers

Site	Comments
1[a]	Increased yield and healthy trees.
3[b]	Increased flowering, cherelle and pod production.
4[b]	Very significant difference in trees, harvest and yield. Clearly very high increase in yield.
7	Fertilised trees bearing more pods than unfertilised trees.
8[a]	Change in leaf colour to green and healthy, and increase in flower and cherelle production. An increase in pods is predicted after NPK application.
9	Cocoa was heavily bearing fruits and healthy
10	Change in leaf growth and vegetative health and improvement of tree bark. Increased pod production from about 0.5–1 bag to about 2.5 bags of wet bean.
12	Leaf flush, flowering improved. Cherelle and production of ripe pods increased.
13	Leaf changed to green. Flower setting, cherelle and pod load increased.
16	Many flowers on stem. New fan branches after tipping.
18[a]	An increase in production responding to the application.
21	Cocoa production went up. Leaves changed from yellow to green. (Note: grower does not recommend fertiliser due to cost.)
24[b]	Cocoa trees were healthy. Heavy pod load, flowering heavy and healthy leaves.
25	Increase in pod number, healthy leaves. Trees had healthy branches.
27	Leaves turn evergreen. Trees put on more flowers.
31	Evergreen healthy trees. Bearing on trees from stem to secondary branches. Hot sun in the valley causes trees to lose leaves.
32[b]	Healthy growth of trees. Trees bearing big pods.
41	Decrease in black pod incidence. Tree health improved. Increase in production (integrated pest and disease management block).
46	Healthy evergreen trees with many flowers and then pods.
50	Conflicting comments: ‘Cocoa trees grew healthy, green and fast’ versus ‘Did not observe any difference (one application after planting)’.

NPK = fertiliser containing nitrogen, phosphorus and potassium
[a] A Cocoa Coconut Institute block
[b] A plantation

Soil and plant nutrient status

Although there have been previous surveys in PNG of cocoa leaf nutrient concentrations and soil analyses (leaf: Southern and Dick 1969; soil: Bleeker and Healy 1980; Bleeker 1983; Freyne et al. 1996; Hanson et al. 1998), this is the first that has analysed soil and cocoa leaf from the same locations, as well as compiled information on block management and history. As far as we are aware, it is also the first time that pod nutrient concentrations and leaf nutrient concentrations for different clones have been reported for PNG.

Leaf nutrient contents

Leaf analysis has been less useful for the diagnosis and management of nutrition problems in cocoa than for other crops. This is because leaf age and light intensity usually override the nutritional effects on leaf nutrient composition, except when there are marked deficiencies (Wessel 1985). We have used the values in Table 6 for categorising leaf nutrient concentrations as deficient or not. For trace elements, the values were based on the survey and review by Southern and Dick (1969). These values have only ever been described as 'tentative' because they have not been verified by trials in PNG. Most other values reported in the literature originate from the Ivory Coast (Loué 1961) or Trinidad (Murray 1967), and are summarised by Wessel (1985) and shown for comparison in Table 7. The leaf nutrient concentrations are shown in Table 8, with values for N, K, P and Fe also shown as maps in the Appendix (Figure A1). It should be noted that although concentrations of a particular element may not be deficient at the time of sampling, correction of other deficiencies may cause that element to become deficient in the future. N appeared to be deficient at almost all sites, and correction of N deficiency is likely to result in deficiency of other elements.

At most sites leaves appeared deficient in N, except for two sites in East Sepik province and one in West Sepik province. Leaf N:P ratios were low, with a mean of 10.4 (range 6.5–17.4, with only three sites > 15), indicating a deficiency of N relative to P at most sites.

At only 10% of sites did leaves appear deficient in K. This was surprising as K deficiencies have been reported, particularly on coralline soils, and many sites in this study had low soil exchangeable K contents and high ratios of exchangeable Ca:K or Mg:K. Two possible reasons for the discrepancy are that a) the critical leaf value is not realistic, or b) K deficiency is not expressed because another deficiency (e.g. N) is limiting.

Table 6. Suggested values for cocoa leaf nutrient concentrations in Papua New Guinea

Element	a	b	c
Nitrogen (%)	2.0	2.3	3.0
Phosphorus (%)	0.12	0.16	0.30
Potassium (%)	1.1	1.6	2.6
Calcium (%)	0.5	0.8	2.6
Magnesium (%)	0.3	0.4	1.0
Sulfur (%)	0.02	0.03	0.10
Manganese (mg/kg)	15	30	
Iron (mg/kg)	30	50	
Copper (mg/kg)	4.0	6.0	
Zinc (mg/kg)	20	30	
Boron (mg/kg)	15	25	

kg = kilogram; mg = milligram
Note: Values are based on the third leaf of a recently hardened leaf flush at mid-canopy height, with values defined as: deficient (< a), subnormal (a–b), tentative critical level (b), normal (b–c), above normal (> c).
Source: Fahmy (1977)

At most sites leaf Ca concentrations were adequate, with only a few sites in New Ireland, Madang, Northern and West Sepik provinces showing deficient levels.

Leaf Mg concentrations were adequate in all provinces except for East New Britain, where over 60% of the sites had deficient levels. Exchangeable Mg contents generally appeared adequate in East New Britain soils, but Mg uptake may be limited due to the low ratios of exchangeable Mg:K.

Leaf P concentrations were not clearly related to province. The 15 sites with low or deficient levels of

P were spread over all provinces. Those sites also generally had high N:P ratios.

At no sites did leaves appear deficient in S. The critical level of 0.02–0.03% suggested by Fahmy (1977) is much lower than that used for many other crops (often about 0.15%), so should be treated with caution. However, even if a critical level of 0.15% is assumed, most of the sites appeared to have adequate leaf S concentrations. Hartemink and Bourke (2000) comment that S deficiency is common in a number of other crops in PNG and occurs in a range of different soil types. The common causal factors of S deficiency are high rainfall, leaching and loss of S through frequent burning of vegetation. This suggests that there is the potential for S deficiency to occur in cocoa crops, necessitating the establishment of reliable critical levels of S.

At most sites leaves had deficient or subnormal Fe concentrations compared to the published tentative critical levels. Southern and Dick (1969) reported that Fe deficiency symptoms are common in cocoa and have been widely reported in the field. They found that 75% of the cocoa sampled showed Fe deficiency symptoms with leaf levels < 50 mg/kg Fe, and noted that in some cases, where symptoms were severe, leaf levels were < 40 mg/kg. In the current study, over 70% of leaf samples had levels < 40 mg/kg. To what extent mild Fe deficiency will affect yields is unknown, but severe deficiency will cause defoliation, die-back and low yields (Southern and Dick 1969). It is imperative that the critical level for Fe be reassessed, to determine if Fe deficiency is widespread or not.

At only a few sites did leaves appear deficient in Mn, B, Cu or Zn. There was a wide variation in leaf Mn concentrations. Southern and Dick (1969) also commented on the wide range of concentrations of Mn in cocoa leaf in PNG. They noted that severe Mn deficiency symptoms were observed at 15 mg/kg Mn, and recognisable symptoms at 20 mg/kg. In our study, the lowest leaf Mn level was 25 mg/kg and the overall average was quite high at 176 mg/kg. Bleeker (1983) noted that low leaf Fe was often associated with high leaf Mn, but there did not appear to be any relationship between concentrations of these two elements in our dataset. Leaf Mn concentration was significantly correlated with soil pH (r = –0.3), with the highest values generally occurring at a soil pH_{water} of < 6.0. Southern and Dick (1969) found low Mn values in neutral to alkaline soils of alluvial origin. They also observed that deficiency symptoms of Zn, B and Cu were rarely observed in cocoa in PNG, which is supported by our dataset, with very few leaf samples having concentrations of these elements below levels considered critical.

There were significant correlations between many leaf nutrient concentrations. The largest correlation coefficients were between Mg and Zn (+0.63), Mg and K (–0.66), and P and Ca (–0.53).

Leaf size and dry matter content in relation to nutrient content

Wessel (1985) reported that the dry matter content of leaves increases with leaf age and thus may affect nutrient concentration when expressed as a dry

Table 7. Nutrient concentrations (% of dry matter) in deficient and normal cocoa leaves

Nutrient	Criteria according to Loué (1961)			Criteria according to Murray (1967)		
	Severely deficient	Moderately deficient	Normal	Deficient	Low	Normal
Nitrogen (%)	<1.80	1.8–2.0	2.35–2.50	<1.8	1.8–2.0	>2.0
Phosphorus (%)	0.08–0.10	0.10–0.13	>0.18	<0.13	0.13–0.20	>0.20
Potassium (%)	<1.0	1.0–1.2	>1.2	<1.2	1.2–2.0	>2.0
Calcium (%)				<0.3	0.3-0.4	>0.4
Magnesium (%)				<0.20	0.20–0.45	>0.45
				Criteria according to de Geus (1973)		
Fe (mg/kg)				50		65–175
Zn (mg/kg)				15–20		30–65
B (mg/kg)				8.5–11		25–75

kg = kilogram; mg = milligram
Source: Wessel (1985)

Table 8. Nutrient concentrations of cocoa leaves from each province

Nutrient level	Province[a]									
	ENBP (11)	ARB (9)	NIP (9)	MaP (8)	ESP (8)	MoP (6)	NP (6)	WSP (4)	WHP (1)	All (62)
N minimum (%)	1.6	1.4	1.5	1.9	2.1	1.6	1.6	2.0		1.4
N maximum (%)	2.2	2.0	2.2	2.1	2.5	1.9	2.0	2.4		2.5
N mean (%)	2.0	1.7	1.9	2.0	2.3	1.8	1.7	2.2	2.0	1.9
Sites ≤ 2.3% N[b]	100%	100%	100%	100%	75%	100%	100%	75%	100%	95%
P minimum (%)	0.16	0.15	0.13	0.11	0.14	0.12	0.15	0.19		0.11
P maximum (%)	0.23	0.26	0.26	0.26	0.22	0.20	0.22	0.23		0.26
P mean (%)	0.20	0.19	0.20	0.19	0.18	0.17	0.19	0.22	0.25	0.19
Sites ≤ 0.16% P	9%	33%	22%	38%	38%	38%	17%	0	0	24%
K minimum (%)	1.9	1.6	1.3	1.9	1.4	1.9	1.6	1.7		1.3
K maximum (%)	2.6	2.3	2.3	2.3	2.2	2.1	2.5	2.1		2.6
K mean (%)	2.3	2.0	1.9	2.1	1.8	2.0	2.0	1.9	2.0	2.0
Sites ≤ 1.6% K	0	11%	22%	0%	25%	0	17%	0	0	10%
Ca minimum (%)	0.9	1.3	0.7	0.8	1.0	1.2	0.7	0.8		0.7
Ca maximum (%)	1.6	2.2	1.9	2.0	1.8	2.6	2.0	1.8		2.6
Ca mean (%)	1.2	1.6	1.3	1.5	1.3	1.9	1.4	1.2	1.3	1.4
Sites ≤ 0.8% Ca	0	0	11%	13%	0	0	33%	25%	0	8%
Mg minimum (%)	0.33	0.41	0.46	0.38	0.42	0.44	0.43	0.44		0.33
Mg maximum (%)	0.61	0.67	0.66	0.59	0.61	0.74	0.80	0.66		0.80
Mg mean (%)	0.42	0.52	0.59	0.49	0.50	0.56	0.55	0.53	0.66	0.52
Sites ≤ 0.4% Mg	64%	0	0	13%	0	0	0	0	0	13%
S minimum (%)	0.19	0.20	0.20	0.14	0.17	0.13	0.12	0.18		0.12
S maximum (%)	0.26	0.22	0.25	0.18	0.23	0.23	0.18	0.20		0.26
S mean (%)	0.22	0.21	0.22	0.16	0.21	0.20	0.15	0.19	0.17	0.20
Sites ≤ 0.03% S	0	0	0	0	0	0	0	0	0	0
Mn minimum (mg/kg)	32	143	173	25	67	42	96	44		25
Mn maximum (mg/kg)	430	700	350	119	210	420	189	250		700
Mn mean (mg/kg)	98	307	299	72	144	194	125	182	168	176
Sites ≤ 30 mg/kg Mn	*0*	*0*	*0*	*12%*	*0*	*0*	*0*	*0*	*0*	*2%*
Fe minimum (mg/kg)	28	24	27	21	23	39	26	33		21
Fe maximum (mg/kg)	97	54	37	43	109	145	33	53		144
Fe mean (mg/kg)	46	31	31	31	42	67	29	41	42	38
Sites ≤ 50 mg/kg Fe	*82%*	*89%*	*100%*	*100%*	*88%*	*67%*	*100%*	*100%*	*100%*	*89%*
Zn minimum (mg/kg)	27	27	47	46	26	35	25	41		25
Zn maximum (mg/kg)	98	89	142	74	96	86	108	71		142
Zn mean (mg/kg)	49	62	87	60	56	62	47	55	81	61
Sites ≤ 30 mg/kg Zn	*18%*	*22%*	*0*	*0*	*25%*	*0*	*50%*	*0*	*0*	*15%*
Cu minimum (mg/kg)	5.1	6.3	8.3	7.2	8.2	7.0	4.5	6.9		4.5
Cu maximum (mg/kg)	9.2	12.5	13.2	13.5	9.6	10.0	15.7	9.1		15.7
Cu mean (mg/kg)	7.0	8.5	11.0	9.7	8.9	8.1	8.6	8.3	11	8.8
Sites ≤ 6.0 mg/kg Cu	*27%*	*0*	*0*	*0*	*0*	*0*	*17%*	*0*	*0*	*6%*
B minimum (mg/kg)	33	32	31	31	26	22	24	24		22
B maximum (mg/kg)	45	44	40	39	41	52	38	39		52
B mean (mg/kg)	38	37	35	34	32	38	33	32	27	35
Sites ≤ 25 mg/kg B	*0*	*0*	*0*	*0*	*0*	*17%*	*0*	*25%*	*0*	*3%*

ARB = Autonomous Region of Bougainville; B = boron; Ca = calcium; Cu = copper; ENBP = East New Britain province; ESP = East Sepik province; Fe = iron; K = potassium; MaP = Madang province; Mg = magnesium; Mn = manganese; MoP = Morobe province; N = nitrogen; NIP = New Ireland province, NP = Northern Province; P = phosphorus; S = sulfur; WHP = Western Highlands province; WSP = West Sepik province; Zn = zinc

[a] Number of sites in each province is given in brackets.

[b] Critical values for each nutrient from Table 6.

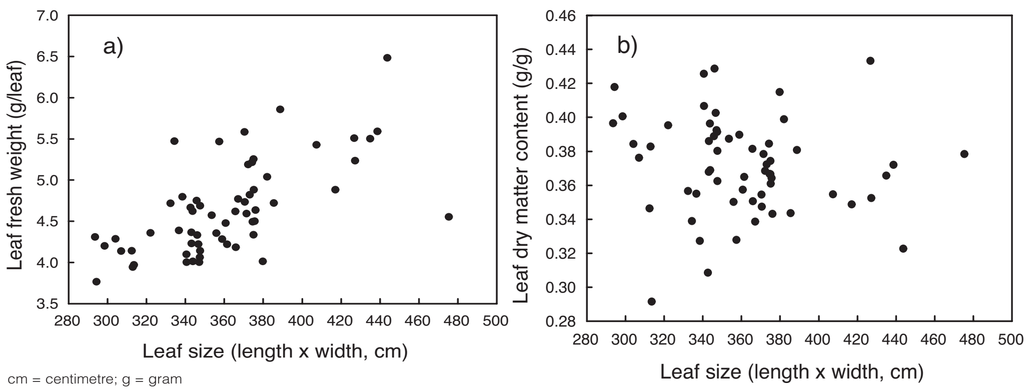
weight. Samples from the survey ranged in dry matter content from 0.29 to 0.43 as a proportion of fresh weight. While there appeared to be a reasonable relationship between fresh weight of leaves and leaf size (length × width), there was little relation between leaf size and dry matter content (Figure 2). This suggests that leaves expand to near full size early in development and then accumulate dry matter as they mature.

The accumulation of dry matter with age may also explain the negative relationship between leaf K concentration and dry matter content (Figure 3). There was a similar pattern with leaf P but not leaf N. However, comparing the total leaf K content with dry matter content shows a flat response (Figure 3). This suggests that K is accumulated in the leaf as it expands but remains the same as dry matter is accumulated, which implies that it may be better to express K concentration on the basis of fresh weight rather than dry weight. However, doing so did not improve the relationship between leaf K and soil K. Alternatively, the leaf K could be adjusted to a common dry matter content but, again, this did not improve the relationship between leaf K and soil K. Similarly, adjusting for dry matter did not improve the relationship between leaf P and soil P.

Most of the leaf parameters were quite consistent across all sites and also when grouped by province (Table 9). The only exception is the number of leaves per flush, which was very low in Morobe province compared with the others. A comparison was also done by landform but, again, the parameters were consistent among those categories.

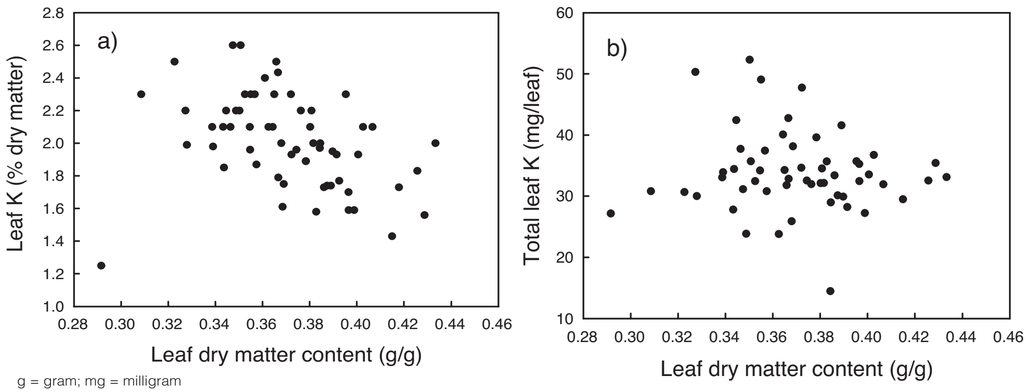
Soil physical properties

Most of the soils sampled in each province were similar to the general descriptions given by Bleeker



cm = centimetre; g = gram

Figure 2. Relationship between leaf size (length × width, cm) and (a) leaf fresh weight and (b) dry matter content



g = gram; mg = milligram

Figure 3. Relationship between leaf dry matter content and (a) leaf potassium (K) concentration and (b) total leaf K

and Freyne (1981). In East New Britain province, most soils are volcanic ash soils and have medium to coarse textures (Bleeker and Freyne 1981). All soil profiles sampled in this survey progressed from a loam surface to sandy loam or clayey loam subsoils, with one exception, site 63, which had a clay loam surface and medium clay with mottles at depth.

On Buka Island (sites 8–11) in the Autonomous Region of Bougainville, the soils were predominantly reddish clay soils, while on Bougainville Island they tended to have very dark loam topsoils and clay subsoils, with two sites (14 and 15) having sandy subsoils. All soil profiles in New Ireland province tended to be shallow with very sticky reddish brown clay soils. In some profiles there was evidence of small shells and limestone fragments, and in others mottles and cemented layers, indicating impeded drainage. Most of the sites sampled in Morobe province were situated around or to the west of Lae. Bleeker and Freyne (1981) describe these soils as generally having fine–medium textures, sometimes with interbedded sandy layers. In this study, soils sampled in this region generally fitted this description and had loam, silty loam or clay loam surfaces and progressed to either clay loams or more sandy loam subsoils.

Most of the samples collected in Northern Province were from the Mt Lamington–Kokoda area, and were predominantly brown to grey-brown sandy loams to clayey sands; small stones and rocks were commonly encountered below the surface layers. Bleeker and Freyne (1981) describe the soils in Madang province as being generally fine-textured. In this survey, the two sites situated on Karkar Island (42 and 43) had shallow profiles, coarse sandy loamy textures and volcanic rock fragments throughout the profile below about 30 cm. The rest of the sites sampled on the mainland were all fine-textured, varying from clay or clay loam surface soils to light to medium clay subsoils. The presence of gleyed mottling at site 45 suggests poor drainage.

The soils in East Sepik province were variable but fitted the general description provided by Bleeker and Freyne (1981), being young alluvials with firm to friable clay and silty clay topsoils overlying stratified layers ranging from friable to firm sandy-clay loams to clays. Evidence of poor drainage was common, with many profiles having yellowish-brown, brown to light grey mottles at depth. The soils in West Sepik province were generally fine textured with loam and clay loam to light-clay textures. Only two sites were sampled in Western Highlands province and both had clay loam to clay textures and mottling below 30 cm. Site 61 was very stony throughout the entire profile.

Root growth of cocoa is strongly influenced by the texture and structure of the soil profile (Bleeker and Freyne 1981; Freyne et al. 1996). Wood (1985) suggested that the ideal soil for taproot penetration and lateral root distribution needs to be composed of approximately 30–40% clay, 50% sand and 10–20% silt, but more important is the vertical distribution of textures throughout the soil profile. Freyne et al. (1996) classified 63 soils from 12 provinces into six major types depending on their effects on root devel-

Table 9. Cocoa leaf parameters by province

Leaf parameter	Province[a]										
	ENBP (11)	ARB (9)	NIP (9)	MaP (8)	ESP (8)	MoP (6)	NP (6)	WSP (4)	WHP (1)	Mean[b]	cv(%)[b]
Leaf shape (length/width)	2.8	2.8	2.8	2.8	2.9	2.8	2.7	3.0	2.7	2.8	6.5
Leaf size (length × width, cm^2)	381	366	349	352	350	352	383	339	407	361	10.4
Fresh mass (gram/leaf)	5.0	4.7	4.9	4.4	4.3	4.4	4.9	4.3	5.4	4.7	12.1
Dry mass (gram/leaf)	1.8	2.0	1.7	1.6	1.7	1.7	1.8	1.6	1.9	1.7	11.9
Dry mass/fresh mass	0.36	0.42	0.35	0.37	0.39	0.39	0.37	0.37	0.35	0.37	7.9
Leaves per flush	4.2	3.4	3.5	3.6	3.3	1.3	3.8	2.7	6.0	3.4	43.0

ARB = Autonomous Region of Bougainville; cv = coefficient of variation; ENBP = East New Britain province; ESP = East Sepik province; MaP = Madang province; MoP = Morobe province; NIP = New Ireland province, NP = Northern Province; WHP = Western Highlands province; WSP = West Sepik province

[a] Number of sites in each province is given in brackets.

[b] Mean and cv are calculated on each of the 61 sites. Site 8 was excluded from the analysis as it had extreme values for some parameters.

opment. Soils from this study were classified into these six types (Table 10) according to their texture and observations made in the field during sampling. It was estimated that approximately 42% of the sites had soils with little physical limitation to root growth; these were predominantly found in East New Britain, Morobe and Madang provinces. The major soil characteristics encountered that could negatively impact on root growth were heavy texture (group 3), found mainly in the Autonomous Region of Bougainville and New Ireland province, and the presence of gravel and stones (group 4), which was most common in Northern Province. The study of Freyne et al. (1996) had a very similar proportion of sites in each of the six types, as was found in this study.

Soil chemical and biological fertility

Assessing soil fertility is difficult due to the complexity of the chemical, physical and biological factors involved. The effect of soil physical factors on cocoa root growth were comprehensively assessed by Freyne et al. (1996). Several attempts have been made to provide critical values for soil chemical factors relevant to PNG (Table 11).

There are no critical values for Colwell P for cocoa. Suggested critical levels for P based on the Olsen P method vary from 6 to 20.6 mg/kg (Table 11). Although results from the Colwell and Olsen methods are correlated, conversion ratios over a wide range of soils (Colwell = Olsen × 1.6 for sands, × 2.0 for loams and × 3.0 for clay loams and clays) are indicative only (Victorian Department of Primary Industries 2005). Generalised interpretation guidelines for Colwell P suggest critical values ranging from 20 to 50 mg/kg for a soil with low P status and moderate phosphate sorption characteristics, depending on crop demand (Moody and Bolland 1999). In addition to the critical values in

Table 10. Grouping of sites according to their capacity to support root development

Category	Sites by province
Type 1: Soils with no physical limitation to root development within 1.5 m of the surface	East New Britain: sites 1, 2, 3, 4, 5, 6, 7 Bougainville: sites 14, 16 New Ireland: sites 21, 23 Morobe: sites 29, 30, 31, 32, 33 Northern: site 35 Madang: sites 41, 46 47, 48 East Sepik: sites 51, 57, 60 West Sepik: sites 55, 59
Type 2: Soils with imperfect to poor drainage resulting in restricted taproot development	East New Britain: sites 26, 27, 28 Bougainville: site 2 East Sepik: sites 50, 53, 54 Western Highlands: site 62
Type 3: Soils with heavy texture and/or poorly structured subsoils restricting root development	East New Britain: site 63 Bougainville: sites 8, 9, 10, 13 New Ireland: sites 17, 18, 20 Madang: sites 44, 45 East Sepik: sites 49, 52 West Sepik: site 56
Type 4: Soils with a high content of gravel and/or stones within 1 m of the surface	Bougainville: sites 12, 15 New Ireland: site 24 Morobe: site 34 Northern: sites 36, 37, 38, 39, 40 Madang: sites 42, 43 West Sepik: site 58 Western Highlands: site 61
Type 5: Soils with a hardpan, concretionary or indurated layer within 1 m of the surface	New Ireland: site 25
Type 6: Soils < 1 m in depth, overlying bedrock or weathering parent material	New Ireland: site 22

Source: Freyne et al. (1996)

Table 11, Bleeker (1983) recommended exchangeable Ca:K and Mg:K ratios of < 20 and < 10, respectively, for adequate K supply.

In this study, most of the soils could be considered reasonably fertile, with high exchangeable cation contents and desirable pH (Table 12). Soil pH_{water} was > 5 at most sites (0–0.15 m depth). pH_{CaCl2} was about 0.6 units less than pH_{water} (pH_{CaCl2} = 0.99 pH_{water} – 0.61, r^2 = 0.90, over all depths). CEC was > 12 $cmol_c$/kg at most sites (0–0.15 m depth) and was related to pH_{water} at the same depth (r^2 = 0.39, $P < 0.01$), with the lowest values occurring in the most acidic soils. Anion exchange capacity was less than 3 $cmol_c$/kg in all samples. Organic C content covered a wide range, from 1.4% to 8.1%, with a mean C:N ratio of 11 (0–0.15 m depth). Sites 51 and 60 had particularly low C contents. $PBI_{0–15cm}$ covered a wide range, from very low (< 70) to high (> 280). PBI and PSI were closely related ($PBI_{0–15cm}$ = 90.221Ln × $PSI_{0–15cm}$ – 311.3, r^2 = 0.99). Exchangeable K and Mg covered a wide range (Table 12). Soils in New Ireland province (usually developed on raised coral) were generally acidic, with low exchangeable K contents (0–0.15 m depth). Soil pH, CEC, exchangeable K, total N and Colwell P (0–0.15 m depth) are mapped in the Appendixes (Figure 1A).

An active and balanced biological community is a critical component of soil fertility. Biological parameters were not measured, but biological activity is known to be determined principally by soil organic matter content (reported here as organic C) and the physical environment (water and air supply), and to a lesser extent by pH. The higher the organic matter content and aeration, the higher the biological activity; whereas water content and pH have optimum levels, around field capacity for water content and neutral for pH. Most of the soils examined had good conditions for biological activity, at least in the topsoil.

Relationships between all soil parameters at all depths were examined by principal component analysis. The results showed several sites or groups of sites that stood out from the others: one site with a particularly high organic C content in Northern Province; a group of sites with high CEC and exchangeable Ca contents, mostly in Morobe province; one site with high salinity and exchangeable Na near the coast in New Ireland province; and

Table 11. Suggested soil 'critical' values (0–0.15 m depth) for cocoa in Papua New Guinea based on existing literature

Soil parameter	Fahmy (1977)[a]			Bleeker and Freyne (1981)[b]			Hardy, (1958)[b]
		Adequate			Adequate		Adequate
pH		5.5–6.5			6–7.5		na
Nitrogen (%)		>0.20			na		>0.2
Organic carbon (%)		>5			>3.5		>3.5
Carbon:nitrogen		8–10			na		>9
Base saturation (%)		na			na		> 5
Calcium/magnesium		na			na		<4
(Calcium + magnesium) / potassium		na			na		>25
	Low	Medium	High	Low	Medium	High	Adequate
Calcium ($cmol_c$/kg)	2–5	5–10	10–20	4	12	24	>8
Magnesium ($cmol_c$/kg)	0.3–1	1–3	3–8	1	3	6	>2
Potassium ($cmol_c$/kg)	0.2–0.3	0.3–0.6	0.6–1.2	0.20	0.35	0.55	>0.24
CEC ($cmol_c$/kg)	6–12	12–25	25–40	12–13 at 0–15 cm; >5 below 15 cm			>12
Phosphorus (mg/kg)	0–5	6–10	>10	20	60	120	>40

CEC = cation exchange capacity; $cmol_c$ = centimoles of charge; kg = kilogram; mg = milligram; na = not available

[a] Methods: 1:5 water pH, cations extracted with ammonium acetate, CEC leached with 10% sodium chloride, Olsen P (0.5 M sodium bicarbonate, pH 8.5, 1:20, 30-minute extraction), Kjeldahl nitrogen, Walkley and Black organic carbon

[b] In this column, 'phosphorus' is Truog P (0.001 M sulfuric acid + 0.3% ammonium sulfate, 1:200, 30-minute extraction).

[c] In this column, 'phosphorus' is Olsen P.

Table 12. Soil chemical fertility (0–0.15 m depth) in each province

	Province[a]									
	ENBP (11)	ARB (9)	NIP (8)	MaP (8)	ESP (8)	MoP (6)	NP (6)	WSP (4)	WHP (2)	All (62)
pH_{water} minimum	5.4	5.0	4.4	6.0	5.8	5.0	5.4	5.2	5.8	4.4
pH_{water} maximum	6.1	7.7	8.0	6.4	7.3	8.2	6.1	6.4	5.9	8.2
pH_{water} mean	5.8	5.9	5.9	6.2	6.5	6.4	5.7	5.8	5.9	6.1
Sites < pH 5.5[b]	*18%*	*11%*	*25%*	*0*	*0*	*17%*	*33%*	*25%*	*0*	*15%*
Exch. Ca min. ($cmol_c$/kg)	9.6	2.7	1.7	16.4	8.1	12.0	7.8	11.3	17.4	1.7
Exch. Ca max. ($cmol_c$/kg)	24.1	20.2	27.0	31.8	36.7	39.9	16.2	24.8	17.7	39.9
Exch. Ca mean ($cmol_c$/kg)	17.7	10.0	14.7	24.9	19.9	25.5	11.2	17.3	17.5	17.5
Sites < 5 $cmol_c$/kg Ca	*0*	*11%*	*25%*	*0*	*0*	*0*	*0*	*0*	*0*	*5%*
Exch. Mg min. ($cmol_c$/kg)	2.06	0.29	0.35	2.64	3.72	2.06	1.56	13.66	2.74	0.29
Exch. Mg max. ($cmol_c$/kg)	5.34	1.96	4.98	9.21	9.55	10.25	3.27	47.02	3.83	10.25
Exch. Mg mean ($cmol_c$/kg)	3.35	1.29	2.66	6.04	5.93	6.35	2.48	31.55	3.28	4.12
Sites < 1 $cmol_c$/kg Mg	*0*	*11%*	*12%*	*0*	*0*	*0*	*0*	*0*	*0*	*3%*
Exch. K min. ($cmol_c$/kg)	1.02	0.05	0.04	0.19	0.03	0.12	0.12	0.42	0.47	0.03
Exch. K max. ($cmol_c$/kg)	3.66	0.81	0.39	1.61	0.58	3.38	0.67	1.41	0.56	3.66
Exch. K mean ($cmol_c$/kg)	2.32	0.39	0.17	0.84	0.20	1.47	0.25	0.79	0.52	0.82
Sites < 0.31 $cmol_c$/kg K	*0*	*33%*	*75%*	*12%*	*88%*	*17%*	*83%*	*0*	*0*	*37%*
CEC min. ($cmol_c$/kg)	11.4	2.7	3.2	17.0	14.8	10.9	9.1	22.1	20.9	2.7
CEC max. ($cmol_c$/kg)	23.3	18.7	31.0	41.8	45.0	46.9	16.1	31.9	23.1	46.9
CEC mean ($cmol_c$/kg)	19.4	10.4	17.7	33.8	27.2	29.8	11.9	25.9	22.0	21.5
Sites <12 $cmol_c$/kg CEC	*9%*	*67%*	*7%*	*0*	*0*	*33%*	*67%*	*0*	*0*	*23%*
Colwell P min. (mg/kg)	17.3	7.1	7.5	9.3	3.1	1.9	9.5	16.5	49.1	1.9
Colwell P max. (mg/kg)	143.0	55.3	120.2	78.7	24.0	57.9	47.1	30.5	127.6	143.0
Colwell P mean (mg/kg)	65.6	22.7	42.0	34.0	13.0	22.1	27.6	25.9	88.4	35.8
PBI min.[c]	47	56	138	76	48	50	80	71	120	47
PBI max.	201	429	423	538	97	556	658	114	132	658
PBI mean	154	145	284	208	74	196	317	92	126	181
Organic C min. (%)	2.53	1.53	2.57	2.02	1.42	2.17	2.48	2.41	3.12	1.42
Organic C max. (%)	3.85	3.48	4.64	5.31	3.70	7.24	8.08	4.63	3.41	8.08
Organic C mean (%)	3.35	2.52	3.49	3.88	2.60	3.83	5.00	3.30	3.26	3.42
Extr. Zn min. (mg/kg)	1.95	0.12	0.26	0.55	0.40	0.30	0.16	0.71	3.14	0.12
Extr. Zn max. (mg/kg)	6.27	4.72	9.73	7.92	12.13	2.64	2.79	0.92	3.43	12.13
Extr. Zn mean (mg/kg)	3.34	1.91	4.53	2.06	2.29	0.88	0.91	0.77	3.29	2.34
Extr. Cu min. (mg/kg)	0.24	0.37	0.49	3.31	0.64	0.57	0.24	2.43	2.72	0.24
Extr. Cu max. (mg/kg)	1.36	2.90	6.42	6.04	2.47	4.58	0.87	3.58	3.61	6.42
Extr. Cu mean (mg/kg)	0.78	1.38	2.66	4.62	1.47	2.59	0.53	2.82	3.20	2.06
Extr. Mn min. (mg/kg)	0.6	2.7	2.5	0.4	3.2	1.9	0.5	6.1	23.3	0.4
Extr. Mn max. (mg/kg)	29.2	126.1	144.0	18.4	28.3	8.4	9.7	13.2	34.8	144.0
Extr. Mn mean (mg/kg)	7.9	41.5	48.6	10.0	12.4	4.8	3.3	10.7	29.0	19.0
Extr. Fe min. (mg/kg)	14.7	7.7	13.2	43.2	11.3	5.4	8.2	63.5	80.0	5.4
Extr. Fe max. (mg/kg)	54.2	35.0	58.4	83.4	68.4	65.2	71.6	130.1	118.5	131.0
Extr. Fe mean (mg/kg)	35.3	21.6	32.6	53.9	36.4	39.3	30.9	93.2	99.3	41.3
$CaCO_3$ equiv. max. (%)[d]	6.8	3.0	44.6	0	6.6	16.0	0	0	0	44.6

ARB = Autonomous Region of Bougainville; C = carbon; $CaCO_3$ = calcium carbonate; CEC= cation exchange capacity; $cmol_c$ = centimoles of charge; Cu = copper; ENBP = East New Britain province; equiv. = equivalent; ESP = East Sepik province; exch. = exchangeable; extr. = extractable; Fe = iron; K = potassium; kg = kilogram; MaP = Madang province; max. = maximum; mg = milligram; min. = minimum; Mn = manganese; MoP = Morobe province; NIP = New Ireland province, NP = Northern Province; P = phosphorus; PBI = phosphate buffer index; WHP = Western Highlands province; WSP = West Sepik province; Zn = zinc

[a] Number of sites in each province is given in brackets.

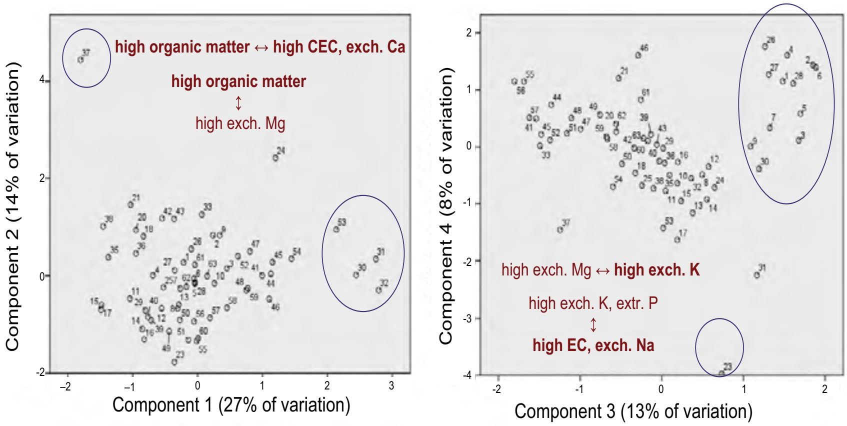
[b] Critical values for each parameter are from Table 11.

[c] PBI ratings: < 35 very, very low, 36–70 very low, 71–140 low, 141–280 moderate, 281–840 high, > 840 very high

[d] Minimum and mean not determined because samples with pH_{water}< 6.5 (which existed in all provinces) were not analysed. Minimum is probably zero in all provinces.

a group of sites with high exchangeable K contents, mostly in East New Britain province (Figure 4, Table 13).

Many of the sites had ratios of exchangeable cations considered unfavourable for K uptake; 75% of sites had Ca:K ratios > 20 and 45% had Mg:K ratios > 10.



Ca = calcium; CEC = cation exchange capacity; EC = electrical conductivity; exch. = exchangeable; extr. = extractable; K = potassium; Na = sodium; P = phosphorus

Figure 4. Grouping of sites by soil chemical properties using principal component analysis

Table 13. Sites or groups of sites that had soil chemical properties distinct from the other sites

Site	Province	Local level government	Name of block
High organic matter content (>3.5% carbon, > 0.25% nitrogen throughout profile)			
37	Northern	Kokoda	Ombite
High exchangeable calcium (> 25 $cmol_c$/kg throughout profile)			
30	Morobe	Wampar	Ngawapog
31	Morobe	Umi–Atzena	Kaput
32	Morobe	Wampar	Block 4
53	East Sepik	Numbo	Hembenjanka
High exchangeable potassium (> 2 $cmol_c$/kg throughout profile)			
1	East New Britain	Central Gazelle	11A-IPDM plot
2	East New Britain	Central Gazelle	11A-IPDM plot
3	East New Britain	Inland Baining	CCI on-farm trial-SG2—hybrid small plot
4	East New Britain	Central Gazelle	Block.8
5	East New Britain	Central Gazelle	5A (mutant segregant studies)
6	East New Britain	Central Gazelle	On-farm trial-Bitavavar (Taliligap)
7	East New Britain	Kokopo–Vunamami	CCI Cocoa Breeding Multilocation Trial
26	East New Britain	Bitapaka	IPDM trial option 1
27	East New Britain	Kokopo–Vunamami	CCI on-farm trial (intermediate plot)
28	East New Britain	Bitapaka	Mangoana project
9	Bougainville	Hagogohe	Ngawapog
30	Morobe	Wampar	Kaput
31	Morobe	Umi–Atzena	
Saline (sodium > 2.5 $cmol_c$/kg, EC > 750 µS/cm, 0–30 cm depth)			
23	New Ireland	West Coast Central	Block 88
High P (> 90 mg/kg Colwell P throughout profile) and micronutrients			
21	New Ireland	Central New Ireland	Besen

$cmol_c$ = centimoles of charge; EC = electrical conductivity

Soil mineralogy

Soil mineralogy varied considerably between sites. Less weathered soils were dominated by glass or feldspar, whereas more weathered soils were dominated by halloysite (kaolinite) and also contained iron oxides (Table 14). The degree of weathering was also evident in the relative contents of Si and Al + Fe (Table 15). As mineralogy was determined for selected sites only, it was not possible to comprehensively analyse the relationships between mineralogy and nutrient status of the soils and plants. However, among the sites sampled, some relationships between soil mineralogy and nutrient status were evident. Soils with the highest glass content also had high exchangeable K contents. Smectite content was positively correlated with exchangeable Ca and Mg contents and with CEC. On the other hand, halloysite content was positively correlated with anion exchange capacity. Allophane content was positively correlated with organic C and N contents.

Of the soils analysed for allophane, most had contents < 2% in the 0.3–0.6 m depth layer, with the

Table 14. Mineralogy of selected sites (0.3–0.6 m depth)

Province Site	Quartz	Amorphous (glass)	Sodium/ calcium feldspar	Calcite	Smectite	Halloysite	Allophane (%)	Other minor
East New Britain								
7	–	D	M	–	–	–	0.8	–
28	T	D	M	–	–	M	1.1	–
63	M	M	T	–	M	D	1.2	H, Go, Cr
Bougainville								
10	M	–	M	–	M	D	0.8	–
15	T	–	D	–	–	–	3.2	–
New Ireland								
17	M	–	–	–	–	D	0.2	Go
22	D	M	M	–	–	–	0.9	Cl, P
24	T	–	–	–	–	D	2.9	Go, Gi
Morobe								
31	SD	M	SD	–	D	–	6.2	Z
33	M	CD	SD	–	CD	T	5.0	Z, Cr, P
34	T	CD	T	–	CD	M	3.4	P
Northern								
37	SD	M	D	–	–	–	10.6	A, Cl
40	M	T	CD	–	–	CD	1.0	A, Cr
Madang								
43	M	D	SD	–	–	–	5.6	P
45	M	M	M	–	D	M	2.7	–
East Sepik								
51	D	T	SD	–	M	–	0.4	–
53	D	–	SD	SD	M	T	0.5	–
60	D	M	SD	–	M	T	1.0	–
West Sepik								
55	D	–	SD	–	M	–	0.7	Cl
58	CD	–	CD	–	M	–	2.1	Cl
Western Highlands								
62	D	–	M	–	M	M	0.6	–

– = not detected; A = amphibole; CD = co-dominant (sum > 60%); Cl = chlorite; Cr = christobalite; D = dominant (> 60%); Gi = gibbsite; Go = goethite; H = haematite; P = pyroxene (augite); SD = subdominant (20–60%); M = minor (5–20%); T = trace (< 5%); Z = zeolite/stilbite/laumontite highest content being 10.6% in Kokoda in Northern Province (Table 14). The high allophane content of that site corresponded with high organic matter content (Table 13). All the sites in Morobe and Madang province had allophane contents between 2.7% and 6.2%. Allophane is very reactive and capable of strongly sorbing phosphate, and allophane content (0.3–0.6 m depth) was significantly correlated with PBI (0–0.15 m depth) ($r = 0.69$). Allophane content was also correlated with pH_{NaF} ($r^2 = 0.61$), so pH_{NaF} could be used to estimate the allophane content of all soils; $pH_{NaF} > 9.5$ was a fairly reliable indicator of the presence of at least some allophane. In Madang, Morobe and Northern provinces, most of the sites had $pH_{NaF} > 9.5$, whereas in East Sepik, West Sepik and Western Highlands provinces no sites had $pH_{NaF} > 9.5$ (Table 16). There was a strong relationship between pH_{NaF} and PBI for soils not containing carbonate (Figure 5).

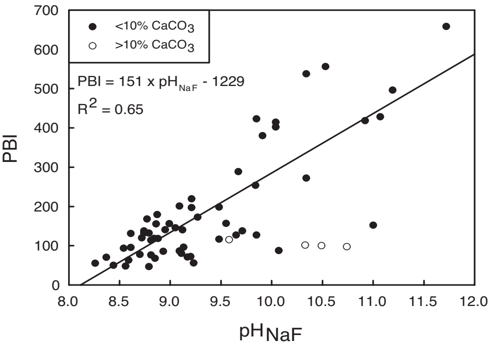
Relationship between leaf nutrient concentrations and soil properties

Principal component analysis showed several relationships between leaf nutrient concentrations and soil parameters (Figure 6). The sites with high

Table 15. Total elemental content of selected sites (0.3–0.6 m depth)

Province Site	Silicon dioxide (SiO_2; %)	Aluminium oxide (Al_2O_3; %)	Iron oxide (Fe_2O_3; %)	Magnesium oxide (MgO; %)	Calcium oxide (CaO; %)	Sodium oxide (Na_2O; %)	Potassium oxide (K_2O; %)	Phosphorus oxide (P_2O_5; %)
East New Britain								
7	61	16.6	5.7	1.62	4.00	3.76	2.25	0.31
28	48	17.4	10.6	4.97	4.36	1.37	1.03	0.24
63	46	26.8	9.8	1.42	2.41	0.98	0.32	0.14
Bougainville								
10	50	23.0	13.3	0.20	0.07	0.01	0.03	0.43
15	69	12.9	8.0	1.99	1.85	1.25	0.80	0.10
New Ireland								
17	33	31.1	15.5	0.50	1.45	0.06	0.08	0.48
22	60	17.8	5.9	1.27	2.89	3.22	2.12	0.23
24	51	15.4	11.2	4.81	4.48	1.86	1.17	0.17
Morobe								
31	37	20.6	15.4	5.48	3.20	0.19	0.81	0.42
33	46	19.6	7.2	3.09	3.43	2.33	0.54	0.45
34	53	21.6	8.3	2.56	3.17	2.61	1.21	0.11
Northern								
37	50	19.8	11.2	3.04	6.95	1.87	0.71	0.28
40	49	18.7	13.5	2.93	3.60	0.67	0.48	0.05
Madang								
43	67	14.1	6.4	1.89	1.52	2.00	0.98	0.07
45	52	13.7	6.9	1.76	10.44	1.15	0.84	0.10
East Sepik								
51	60	16.8	8.5	3.64	1.73	1.99	1.53	0.12
53	60	16.0	8.6	3.66	4.70	3.18	0.81	0.10
60	46	22.1	16.3	0.92	0.90	0.44	0.25	0.11
West Sepik								
55	62	14.9	7.5	3.54	4.40	2.88	1.00	0.12
58	61	17.6	8.6	1.19	0.63	0.95	1.45	0.09
Western Highlands								
62	50	18.2	10.3	5.26	10.24	2.15	0.30	0.11

soil exchangeable K contents had the highest leaf K values. The sites with high soil CEC and exchangeable Ca contents and smectite mineralogy had the highest leaf Ca and B values. The site with high soil organic matter did not have particularly low or high contents of any cations.



$CaCO_3$ = calcium carbonate; PBI = phosphate buffer index

Figure 5. Relationship between PBI and pH_{NaF}

There was a reasonable relationship between soil and leaf nutrient levels for K and P but not for other nutrients. Leaf K concentration increased steeply with increasing soil exchangeable K at low soil concentrations and then reached a plateau (Figure 7a). Leaf K content was also positively correlated with the ratio of exchangeable K:Ca. The relationship between leaf P and soil Colwell P was similar to that between leaf K and soil exchangeable K (Figure 7b). There were no significant relationships between leaf and soil concentrations for other elements.

Bleeker (1983) noted that past nutritional studies of cocoa showed that N deficiencies were common even when soil N status was high, and this was attributed mainly to high light or poor shade conditions. There was no obvious relationship between leaf N and shade conditions in this data set. High soil C:N ratios can also be indicative of plant N deficiencies. However, there was no relationship between leaf N concentration and soil total N content or between leaf N concentration and soil C:N ratio. Most sites had soil C:N ratios (0–0.15 m depth) in the range 7–15, similar to the range (8–14) for PNG soils reported by Bleeker (1983).

Sites that had leaf concentrations below critical levels did not necessarily have soil concentrations below critical levels, nor vice versa. This discrepancy is likely to be due largely to the inadequacy of the 'critical levels' being used for both leaf and soil, which have only ever been described as 'tentative'. There is a clear need to produce reliable critical levels for PNG, particularly for leaf nutrient concentrations. In addition, there are no guidelines for the required levels of soil micronutrient concentrations. In our survey, there appeared to be low or deficient concentrations of Fe in particular, and also Zn and Cu at some sites.

For K and P, however, there was a degree of correspondence between leaf and soil critical values. All sites with leaf K concentrations less than the critical level of 1.6% had soil exchangeable K contents less than the critical level of 0.3 $cmol_c$/kg (Figure 7). In the soils tested, 37% were deficient in K but only 10% of leaf samples were deficient. All sites with leaf P concentrations less than the critical level of 0.16% had soil Colwell P contents less than 25–50 mg/kg, which is the range of critical levels commonly cited for other crops (Moody and Bolland 1999). Approximately 60% of the sites had soil P

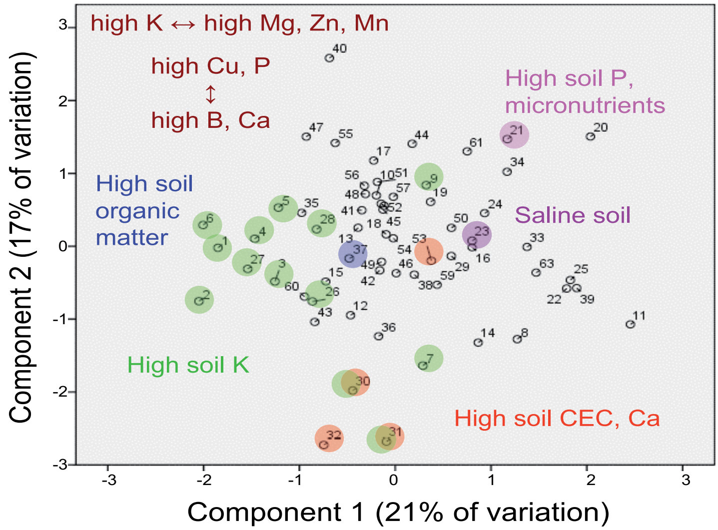
Table 16. pH_{NaF} of soils with < 5% calcium carbonate equivalent (0.3–0.6 m depth) in each province

pH_{NaF} level	Province[a]									
	ENBP (9)	ARB (8)	NIP (7)	MaP (3)	ESP (6)	MoP (3)	NP (6)	WSP (2)	WHP (2)	All (43)
pH_{NaF} minimum	8.74	8.37	8.99	8.88	8.26	8.44	9.11	8.61	8.72	8.26
pH_{NaF} maximum[b]	9.55	11.07	10.04	10.34	8.85	10.49	11.72	8.81	8.74	11.72
pH_{NaF} mean	9.02	9.44	9.66	9.75	8.58	9.60	10.51	8.71	8.73	9.40
Sites with pH_{NaF} >9.5	*11%*	*25%*	*71%*	*67%*	*0%*	*67%*	*67%*	*0%*	*0%*	*37%*

ARB = Autonomous Region of Bougainville; ENBP = East New Britain province; MaP = Madang province; ESP = East Sepik province; MoP = Morobe province; NIP = New Ireland province; NP = Northern Province; WHP = Western Highlands province; WSP = West Sepik province.
[a] Numbers in brackets give the number of sites without $CaCO_3$.
[b] pH_{NaF} > 9.5 indicates the presence of allophane.

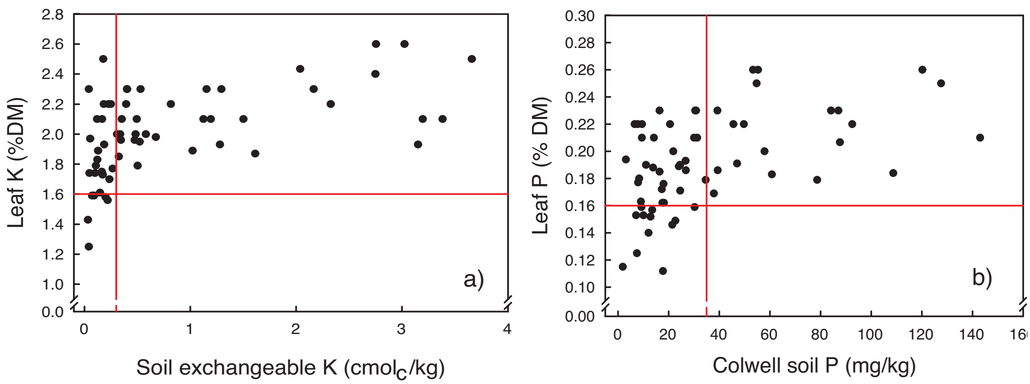
contents below this value. For Mg there was little correspondence between leaf and soil levels; 64% of sites in East New Britain province were classed as deficient in Mg according to leaf analyses but none of these sites had low soil exchangeable Mg contents.

Nutrient interactions, for example between Mg and K, were observed, and this could have further implications for the interpretation of soil and leaf critical levels. Over all sites in all provinces there was a significant correlation between the ratio of soil exchangeable K:Mg and the uptake of leaf Mg



B = boron; Ca = calcium; CEC = cation exchange capacity; Cu = copper; K = potassium; Mg = magnesium; Mn = manganese; P = phosphorus; Zn = zinc

Figure 6. Principal component plot of leaf nutrient concentrations. Coloured circles and labels show site groupings based on principal component analysis of soil properties.



DM = dry matter; kg = kilogram; mg = milligram

Figure 7. Relationship between (a) leaf potassium (K) and soil K (0–0.15 m depth) and (b) leaf phosphorus (P) and soil P (0–0.15 m depth). The red lines show published critical values. For soil P the critical value shown is the median of those established for other crops (25–50 mg/kg), as no critical level for Colwell P has been established for cocoa.

(r = –0.51). A possible implication of this interaction is that as deficient levels of soil K are ameliorated, in cases where leaf Mg may be currently marginal, it may become deficient. This suggests that critical levels may need to be based on nutrient concentration ratios as well as absolute concentrations.

The soil at site 37 (Northern Province) ranged from black clay loam with pH_{CaCl2} 5.3 at the surface (0–15 cm depth) to very dark grey clay loam with pH_{CaCl2} 5.4 at 60–90 cm depth. The mineralogy was dominantly feldspar, with 10.6% allophane. (Photo: Chris Fidelis)

Interactions between nutrient status and other factors

Nutrient status and planting material

There were differences in leaf nutrient concentrations between clones grown at the same site under the same management (Table 17). The clones used as male parents had lower N, K, S, Fe, Mn, B and Zn contents than those used as female parents. Both male parents were classified as deficient in N. Of the female parents, KEE43 had lower Ca, Mg, Fe and Mn concentrations than all the others. All clones had N concentrations around or below the critical concentration, and S concentrations above normal. Other nutrient concentrations were in the normal range.

The differences between clones indicate that it may be possible to select for nutrient uptake properties. However, it would first be necessary to know if leaf nutrient contents are related to nutrient use efficiency (i.e. to total nutrient uptake by the trees and yield). It would also be necessary to know if nutrient uptake traits are inherited from the male, female or both parents.

Nutrient status and management

Some effects of management on nutrient status were detected. Sampling of the option 1 (minimal management inputs) and option 4 (pruning, shade control, weeding, disease control, fertiliser) plots of the IPDM trial at Tavilo showed effects of fertiliser treatment on leaf and soil nutrient contents (Table 18). Fertiliser increased leaf P and K concentrations but not N concentrations. Soil extractable P was increased but exchangeable K content was not. Over the whole dataset there were no clear relationships between leaf N concentration and management factors such as previous fertiliser applications, presence of legumes, shade management or length of time under agricultural production.

Nutrient status and disease

The severity of black pod disease (caused by a *Phytophthora* fungus) was recorded at each site. Almost all sites recorded some level of the disease.

Table 17. Leaf nutrient concentrations of clones in the Cocoa Coconut Institute seed garden at Tavilo, East New Britain province

Clone	Nutrient										
	N (%)	K (%)	Ca (%)	Mg (%)	P (%)	S (%)	Fe (mg/kg)	Mn (mg/kg)	B (mg/kg)	Cu (mg/kg)	Zn (mg/kg)
KA2-106[a]	**1.9**	2.2	1.20	**0.35**	0.19	0.17	**35**	42	35	7.3	33
K82[a]	**1.9**	2.2	1.12	**0.38**	0.18	0.17	**30**	40	38	6.4	**29**
KEE12 [b]	2.3	2.4	1.35	**0.39**	0.19	0.21	**48**	67	43	6.8	34
KEE47[b]	**2.1**	2.3	1.11	0.43	0.23	0.21	**48**	51	42	8.3	41
KEE43[b]	2.3	2.5	0.81	**0.35**	0.22	0.20	**38**	42	42	8.1	38
KEE5[b]	**2.1**	2.5	1.81	0.40	0.21	0.21	**47**	102	45	8.3	41
KEE23[b]	**2.1**	2.3	1.16	**0.39**	0.20	0.20	**46**	54	43	8.1	41
KEE42[b]	**2.2**	2.3	0.96	**0.39**	0.21	0.20	**49**	73	39	8.3	34

B = boron; Ca = calcium; Cu = copper; Fe = iron; K = potassium; kg = kilogram; Mg = magnesium; mg = milligram; Mn = manganese; N = nitrogen; P = phosphorus; S = sulfur; Zn = zinc
[a] Used as male parent in released hybrids
[b] Used as female parent in released hybrids
Note: Deficient or subnormal levels are shown in bold.

As it is known from research with other species that Zn adequacy can increase resistance to some *Phytophthora* infections, the relationship between black pod and Zn levels in leaf and soil was examined. Although low levels of Zn do not necessarily mean that pods will be infected, it appears (apart from one outlier) that pods that are infected come from plants with lower levels of leaf Zn (Figure 8a). Similarly, again with a couple of outliers, it appears that high severity of black pod disease only occurs when soil Zn is low (Figure 8b).

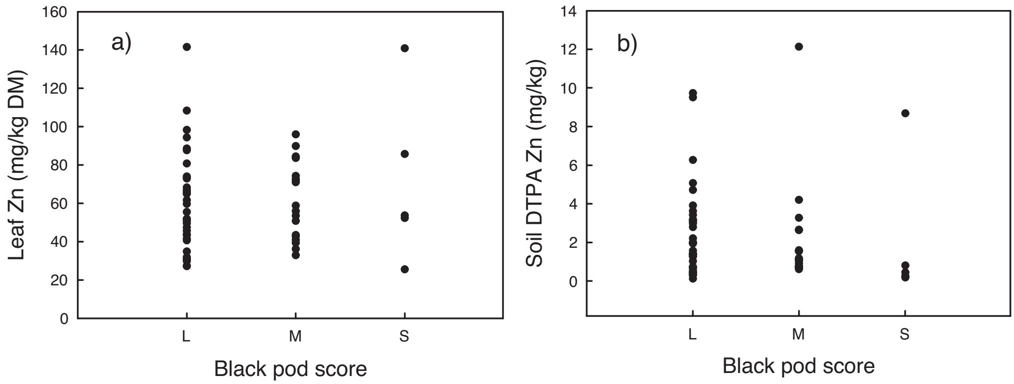
Nutrient status in relation to landforms and agroecological zones

Hanson et al. (1998) used the PNG Resource Information System (PNGRIS) database to define six landform classes: Depositional Floodplains, Depositional Plains and Fans, Volcanic Plains and Fans, Erosional Limestone Plains, Erosional Hills and Erosional Mountains. Sampling sites were allocated to the appropriate landform class and chemical analysis of the soils grouped them according to class to determine if there was any pattern that could be used to classify the landforms in terms of their soil chemistry. For example, although organic C content ranged from 1.4% to 8.1% (Figure 9), there were some patterns with landform class. Depositional Floodplains tended to have the lowest organic C content, with all sites being less than 4%. Similarly, Erosional Hills had values between 1% and 4%. By contrast, Depositional Plains and Fans had the highest and widest range of values. As expected, total N showed a similar pattern to organic C content, with Deposi-

Table 18. Effect of treatment on soil and leaf nutrient concentrations at Tavilo IPDM trial

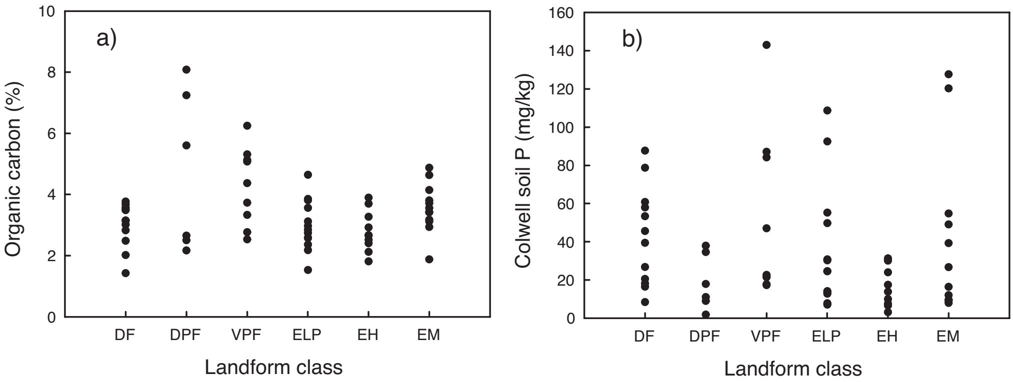
Parameter	Plus NPK fertiliser[a] (site 1)	No fertiliser[b] (site 2)
Leaf N (%)	2.25	2.25
Leaf P (%)	0.21	0.18
Leaf K (%)	2.43	2.30
Soil Colwell P (mg/kg, 0–0.15 m)	88	61
Soil exchangeable K ($cmol_c$/kg, 0–0.15 m)	2.0	2.2
Soil exchangeable K/Ca (0–0.15 m)	8.4	7.7

Ca = calcium; K = potassium; m = metre; N = nitrogen; P = phosphorus
[a] Option 4, including two applications per year of urea (50 g/tree) plus NPK 120 g/tree
[b] Option 11



DM = dry matter; DTPA = diethylene triamine penta-acetic acid; kg = kilogram; L = light; M = medium, mg = milligram; S = severe infection

Figure 8. Relationship between black pod score and (a) leaf zinc (Zn) and (b) soil Zn



DF = Depositional Floodplains; DPF = Depositional Plains and Fans; EH = Erosional Hills; ELP = Erosional Limestone Plains; EM = Erosional Mountains; kg = kilogram; mg = milligram; VPS = Volcanic Plains and Fans
Note: Landform classes from Hanson et al. (1998)

Figure 9. Soil contents of (a) organic carbon and (b) Colwell phosphorus (0–0.15 m depth) for sampled sites grouped by landform class

Table 19. Dominant soil Great Groups in Papua New Guinea Resource Information System mapping units sampled

PNGRIS code	Soil Great Group[a]	Soil description
113	Fluvaquents	Poorly drained, undifferentiated soils with high (≥ 0.2%) or variable organic C contents to ≥ 125 cm
131	Tropofluvents	Mainly well-drained, undifferentiated soils with high (≥ 0.2%) or fluctuating organic C to ≥ 125 cm
141	Troporthents	Undifferentiated, mostly shallow soils typically found in wet climates on moderate to steep slopes
232	Tropofibrists	Swampy, slightly decomposed organic soils with interbedded mineral layers
322	Eutrandepts	Slightly weathered ash soils with high (≥ 50%) base saturation values and thick, black topsoils
324	Vitrandepts	Slightly weathered ash soils with dominantly sandy or gravelly texture and black topsoils
331	Humitropepts	Moderately weathered soils having high organic carbon contents (>+12 kg/m^2) and low base saturation subsoils
333	Eutropepts	Slightly to moderately weathered soils with altered B horizon and high (>+50%) subsoil base saturation values
334	Dystropepts	Moderately weathered soils with altered B horizon and low (≤ 50%) subsoil base saturation values
512	Haplaquolls	Poorly drained, weekly acid to alkaline soils with thick, dark topsoils
520	Rendolls	Shallow, dark, weakly acid to neutral soils formed on calcareous parent material
534	Haplustolls	Weakly acid to alkaline soils with thick, dark topsoils subject to seasonal moisture stress
542	Hapludolls	Weakly acid to alkaline soils with thick dark topsoils and high (≥ 50%) base saturation values
632	Rhodudalfs	Well to imperfectly drained, moderately weathered soils with finer textured bright red subsoils
633	Tropudalfs	Well to imperfectly drained, moderately weathered soils with finer textured subsoils

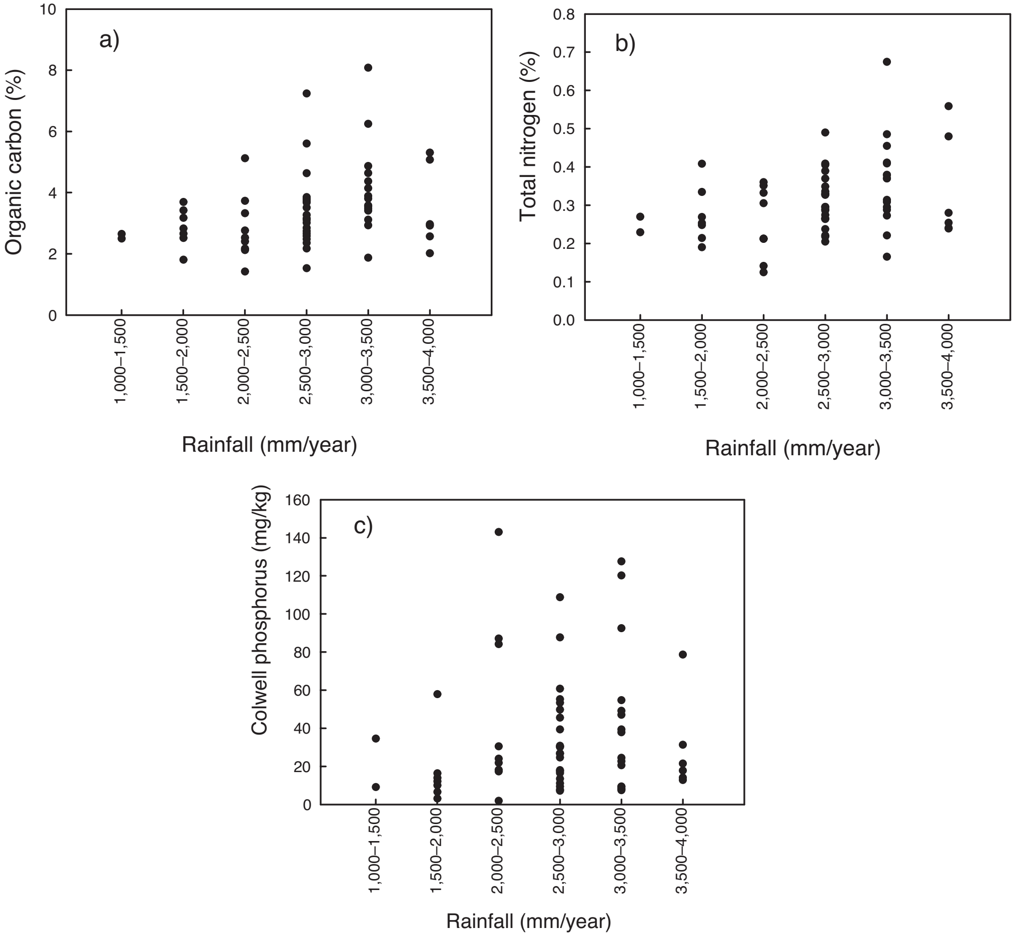
[a] Soil Survey Staff (1975)

tional Floodplains, Erosional Limestone Plains and Erosional Hills generally low and tightly grouped compared with Depositional Plains and Fans. By contrast, Colwell P content was low and tightly grouped in Depositional Plains and Fans in comparison with Depositional Floodplains (Figure 9).

Hanson et al. (1998) separated each landform into agroecological zones based on annual rainfall and rainfall seasonality. However, allocating soil chemical data to agroecological zones did not provide any clearer pattern.

Expressing soil chemical data in terms of rainfall produced some interesting patterns. While the results for organic C, total N and Colwell P covered a wide range at any one rainfall bracket, it was only at the higher rainfall brackets that the higher levels of all three parameters occurred (Figure 10).

The dominant soil Great Group (Table 19) of each mapping unit was also used as a basis to compare site soil chemical characters. Again, some soils showed a strong grouping and others a wide range. For example, there was no overlap in CEC between the Fluvaquents and the Tropofluvents (Table 20) and the two Haplustolls had a very high exchangeable K content compared with most other soils examined. But it was not always so clear-cut; within



kg = kilogram; mg = milligram; mm = millimetre

Figure 10. Relationship between rainfall and (a) organic carbon, (b) total nitrogen, and (c) Colwell phosphorus content of soils (0–0.15 m depth)

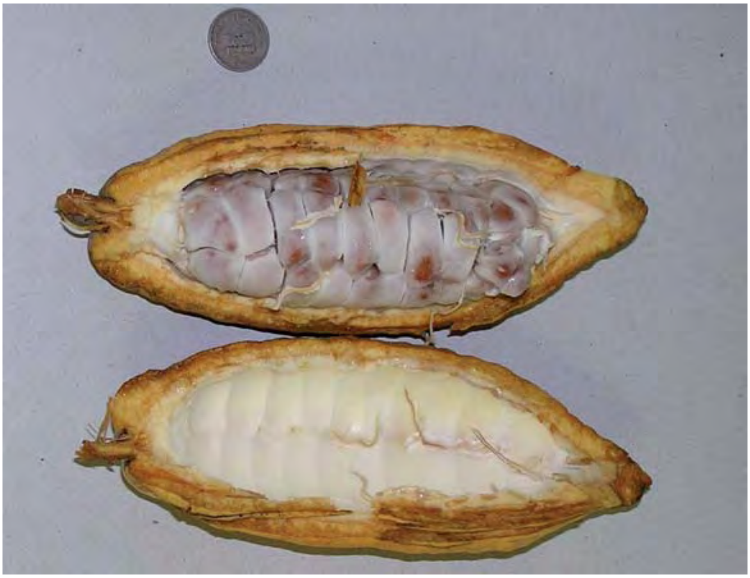
the Tropudalfs, there were two distinct ranges. It should be kept in mind that the allocation of soil Great Groups was made using the version of soil taxonomy that did not yet include the Andisol order (volcanic ash soils). Therefore, most volcanic ash soils fell into the Entisol or Inceptisol orders.

Leaf analysis showed little pattern with respect to dominant soil classification or landform.

Table 20. Range of soil chemical properties according to dominant soil Great Group in relevant Papua New Guinea Resource Information System mapping unit

Soil Great Group	No. sites	pH_{CaCl2}	Organic carbon (%)	CEC ($cmol_c$/kg)	Exchangeable potassium ($cmol_c$/kg)
Dystropepts	8	4.6; 5.1–6.0	2.4–4.9	12; 21–32; 42	0.16–0.19; 0.4–1.0
Eutradepts	10	5.1–6.1	2.2–6.2	9–20; 31	0.12–0.40; 1.2–3.0
Eutropepts	1	5.9	4.1	36	1.2
Fluvaquents	5	5.0–5.3	2.5–5.1	9–15	0.12–0.22; 0.39
Haplaquolls	1	5.6	3.6	30	1.12
Hapludolls	1	6.4	3.7	41	0.58
Haplustolls	2	5.3–7.8	2.5–2.7	11–46	3.2–3.4
Humitropepts	1	5.4	3.1	23	0.47
Rendolls	4	4.1–5.7	2.6–2.9; 3.6–3.8	3–6; 18–21	0.04–0.2
Rhodudalfs	4	4.9–5.8; 7.4	1.5; 2.4–3.1	7; 13–19	0.24–0.81
Tropofibrists	1	4.6	3.5	3	0.05
Tropofluvents	9	5.3–6.1	1.4–3.8 (8.1)	16–24; 40	0.11–0.67; 1.6–2.8
Troporthents	2	4.6–5.3	5.6–7.2	24–40	0.34–0.31
Tropudalfs	12	5.3–7.8	1.8–4.6	15–47	0.07–1.5; 3.2–3.7
Vitrandepts	1	5.0	1.9	8	0.48

CEC = cation exchange capacity; $cmol_c$ = centimoles of charge; kg = kilogram



Cocoa pods sampled for analysis of nutrient content of beans and husks (Photo: John Armour)

Nutrient export

Nutrient exports from blocks, calculated from cocoa pod analyses, were generally within the range measured elsewhere (Hartemink 2005), but were at the low end for N export and higher than the highest previously reported values for K in cocoa beans (Table 21). In this dataset there were no significant relationships between husk or pod nutrient contents and leaf nutrient contents for N, K, Mg or Fe, but there was a significant relationship between husk P and leaf P (husk P = 0.535 × leaf P + 385.6, in mg/kg, $P = 0.01$, $r^2 = 0.69$).

Nutrient exports in cocoa beans are not large in PNG, particularly considering the low yields. However, the nutrient supplying capacity of the soil must run down over time, when other losses are considered (Wessel 1971). To ensure long-term sustainability of cocoa production, the nutrients must be replaced. Of the smallholder blocks surveyed, 85% had been in agricultural production for more than 17 years, with no application of fertilisers, and 62% had been producing cocoa for more than 17 years.

The concentrations of all elements measured in the pods, including heavy metals, are recorded in the Appendix (Table A5).

Table 21. Nutrient removed in dry cocoa beans, assuming a moisture content of 7%

Province	Site	Nutrient removed (kilogram/tonne)					
		Nitrogen		Phosphorus		Potassium	
		Beans	Husks	Beans	Husks	Beans	Husks
World minimum[a]		19.2	10.6	3	1.3	7.5	27.2
World maximum[a]		39.3	31.4	4.6	2.3	10.9	77.2
Bougainville	8	18.8	5.6	4.8	0.8	11.7	27.4
East New Britain	4	17.5	10.3	4.6	1.6	13.6	41.6
East New Britain	63	20.5	5.9	4.6	0.8	11.3	21.8
Madang	44	20.2	13.5	4.9	2.2	11.3	48.7
Morobe	34	17.6	12.1	4.7	1.9	14.0	41.6
New Ireland	18	21.1	10.4	5.0	1.3	14.8	33.2
New Ireland	25	20.3	10.2	3.3	0.7	11.2	29.2
Northern	35	22.1	11.5	4.4	1.4	11.1	40.2

[a] Malaysia, Central America, South America, West Africa, summarised in Hartemink (2005)

Conclusions and recommendations

Conclusions

In this project, insights into possible nutrition-related issues in cocoa production and recommendations for further research were developed. There are major and complex constraints on cocoa production in PNG that are not nutrition-related, and any nutrition research and extension programs must take them into account. The main constraints relate to labour shortages, block maintenance (especially critical following the spread of cocoa pod borer), lack of agronomic knowledge, land shortages, cocoa prices and theft. Many growers in this survey also thought that poor soil fertility and lack of fertiliser application may be constraining productivity.

Most of the cocoa blocks surveyed contained a large variety of crop species and it appears that block management is better when other food crops are present. There were no indications that other species (e.g. legumes as shade trees or groundcover) affected cocoa nutrient status. Of the growers who had used fertiliser (approximately one-third of those surveyed), virtually all reported improvements in growth, flowering and pod production. At the IPDM trial at Tavilo, application of NPK fertiliser has increased leaf K and P concentrations, but not N concentration.

Based on leaf analyses and published tentative 'critical' values, some nutrient deficiencies appear to be common. N and Fe deficiencies in particular appear to be very widespread, with 95% of sampled blocks falling below the critical level for N and 89% for Fe. P deficiencies were encountered in about one-quarter of the blocks sampled. Leaf Mg concentrations were adequate in most blocks in most provinces, except for East New Britain, where 64% of the blocks sampled were deficient. Deficiencies of K, Ca, Mn, B, Cu and Zn were encountered in several blocks (in the range 2–15% of sampled blocks).

It is clear that many of the tentative critical levels proposed for leaf and soil nutrient concentrations have doubtful value for PNG and need to be improved. For example, 64% of sites in East New Britain province were classed as deficient in Mg according to leaf analyses, but none of the East New Britain sites had low content of soil exchangeable Mg. Interactions between Mg and K were observed, and this could have further implications on the interpretation of soil and leaf critical levels. To ensure sustainability of the soil resource and to allow responses to nutrient applications to be assessed properly, appropriate leaf and soil sampling and analytical methodology need to be established and standardised. For future cocoa nutrition research to be effective, correlations and calibration between soil and leaf levels must be developed so that robust diagnostic criteria for soil and leaf testing for cocoa in PNG can be established.

There was a negative relationship between leaf K and P concentrations and leaf dry matter contents, suggesting that leaf K and P contents remained constant while the leaves aged and accumulated dry matter. The relationships between leaf age and nutrient concentrations are important for developing diagnostic criteria.

The sites varied in their physical limitations to root growth. About 42% of sites had no physical limitations to root growth, about 24% were stony or shallow, about 21% had heavy textured or poorly structured subsoils, and about 13% had poor drainage.

Most sites had reasonably high soil CEC, pH and organic C contents. Sites with high soil exchangeable K contents had high leaf K contents, and sites with high CEC and exchangeable Ca contents had high leaf Ca and B contents. There were significant relationships between leaf K and P and the amount of exchangeable K or extractable P in the topsoil. All sites with low concentrations of K or P in the leaves had low soil exchangeable K or extractable P contents, respectively. There was also a significant correlation between leaf Mg concentration and the ratio of soil exchangeable Mg:K.

There appears to be genetic variation in nutrient uptake in planting materials currently being used, suggesting that it may be possible to select for nutrient-use efficiency.

There were no clear relationships between the leaf or soil nutrient contents measured in this study and previously developed categories of landforms and agroecological zones. The lack of relationships is probably due to significant variation on smaller spatial scales than the broad land categories in PNGRIS. There did appear to be a relationship between soil fertility and rainfall, with soil organic C, total N and Colwell P contents tending to be highest in zones with moderately high rainfall.

Cocoa beans from PNG have higher K content than beans from other places, indicating higher export per tonne of beans.

Results were incorporated into a GIS with accurate locations to the individual tree, enabling results to be used for further spatial analysis and future analysis of changes over time.

There are currently widespread nutrient deficiencies, particularly N and also perhaps Fe. In blocks that are being well maintained and regularly harvested, it is quite likely that yield is being constrained by nutrient deficiencies. It is generally agreed that the management of cocoa blocks in PNG must improve dramatically for the cocoa industry to prosper, and perhaps even to survive, particularly in face of the spread of cocoa pod borer. Widespread replanting is also necessary. If these improvements occur, then it is likely that limitations due to nutrient deficiencies will become more important.

Recommendations

The main purpose of the project was to determine what, if any, cocoa nutrition research should be done in PNG. The project identified a high degree of consensus between industry people and scientists with regard to the research that is required.

Recommendations from the workshops held fall into four main categories:

- research to improve understanding of nutrition-related limitations to production
- production of nutrient management recommendations appropriate to different regions
- establishment of effective pathways to adoption
- education and capacity building to ensure continued improvements in nutrient management research and extension.

It will be vital to build impact assessment into the research.

Research to improve understanding

Research should determine the main nutrient limitations to cocoa production in PNG and answer the following questions: Which elements are deficient in which places? What are the amounts of inputs required? What are the most appropriate diagnostic criteria? How serious is nutrient decline under cocoa? What is the nutrient balance in cocoa blocks? The following approaches could be used:

- Thoroughly review past nutrition work in PNG and elsewhere.
- Set up and maintain long-term fertiliser trials in key locations (in particular the three mainland zones) and measure the agronomic and economic responses to fertiliser use. Determine diagnostic criteria. Use uniform planting material, age and shade (light to moderate). Do trials on plantations. Carry out pre-treatment yield recording. Use large plots.
- Survey areas not covered in this survey.
- Locate and resample soil at sites analysed in the past to determine nutrient decline.
- Determine genotype × nutrient use efficiency interactions.
- Determine the importance of shade and cover crops on N nutrition.
- Conduct omission trials to determine which nutrients are limiting (e.g. is Fe deficiency as widespread as the survey indicated?).
- Establish reliable methods for PNG to diagnose nutrient status.
- Examine nursery nutrient management as a means of improving the establishment of trees.
- Examine interactions between cocoa nutrition and cocoa quality.

Production of nutrient management recommendations

Clear nutrient management guidelines should be produced, with different levels appropriate to management levels, aiming for an overall higher level of management (integrated with pest, disease, shade, pruning and weed control). The guidelines should be specific to regions, genotypes, age and planting density. They should also consider interactions with shade or cover crops and inputs of non-fertiliser sources of nutrients. Specific recommendations should be made for growers producing for niche organic markets. The following approaches could be used:

- Produce guidelines for different areas and situations. Start with best-bet guidelines based on current knowledge and then revise them using new data.

- Extend soil and plant tissue surveys to regions not covered in this study.
- Measure the nutrient content of wastes from smallholder households, fermentaries, copra driers and coconut dehusking, which could be applied to cocoa blocks to improve soil fertility.
- Develop a soil and leaf interpretive chart.
- Produce guidelines and protocols for sampling and analytical methods.

Establishment of pathways to adoption

A process for adoption that overcomes the limitations identified by Curry et al. (2007) should be established. Adoption will be a major challenge, even in areas where nutrition is limiting. Methods for adoption must be integrated with other work aiming to overcome constraints on production. The following approaches could be used:

- Establish a limited number of demonstration blocks using carefully selected farmers and ensuring good data collection. Use existing IPDM blocks where possible.
- Carry out economic analysis, including issues of credit, labour availability etc.
- Determine the relevance of 'participatory action research' to PNG cocoa growers.
- Carry out targeted farmer training.
- Recommend strategies such as interplanting with food crops and shade management with replanting activities (vital for improving production).
- Integrate with nucleus enterprise extension models that are being trialled to improve access to processing facilities, transport, credit and training. These models rely on partnerships with commercial service providers, whose profitability is tied to smallholder productivity (Curry et al. 2007). An example of this model is operating successfully at Stockholm in East New Britain province, where Newmark Plantations are providing transport, materials, seedlings and advice to growers in this isolated region. Production has increased from 400 to 3,000 bags/year since the arrangement started. Growers have recently been asking the plantation for fertilisers (McNally, Newmark Plantations, pers. comm.).

Education and capacity building

Capacity should be built within CCI (data processing, field trials, sampling) and within NARI (methods of soil and plant analysis for cocoa). Areas that could be covered include:

- data handling from field to database to reporting
- development of an agronomy procedures manual for CCI

Recommendations for cocoa nutrition research in Papua New Guinea were formulated at the final project workshop in 2008. The workshop involved 53 participants from the industry and research organisations (Photo: Paul Nelson)

- training of the trainers (e.g. attendance at short courses)
- development of alternative laboratory procedures (e.g. mid infra-red analysis)
- development of analytical procedures at NARI
- establishment of sample preparation facilities at CCI
- training, particularly of CCI and NARI officers, in biometrics, spreadsheets, bookkeeping, communication, writing, experimental design
- postgraduate study for CCI agronomists, application for scholarships
- PNG partners obtaining work experience in Australian laboratories and other organisations in PNG
- students from the University of Natural Resources and Environment and Unitech undertaking projects as part of larger research projects.

Appendix
Additional results from the study

Table A1. Locations and names of cocoa sites surveyed and sampled

Site	Owner	Local level government	Name of block	°S[a]	°E[a]
East New Britain province					
1	CCI	Central Gazelle	11A-IPDM option 4 plot	4.30449	152.02510
2	CCI	Central Gazelle	11A-IPDM option 1 plot	4.30484	152.02507
3	SH	Inland Baining	CCI on-farm trial-SG2—small plot	4.36561	151.94316
4	PL	Central Gazelle	Block 8	4.30549	152.04518
5	CCI	Central Gazelle	5A (mutant segregant studies)	4.29982	152.01640
6	SH	Central Gazelle		4.30851	152.03133
7	SH	Kokopo–Vunamami	On-farm trial—Bitavavar (Taliligap)	4.35825	152.22939
26	CCI	Bitapaka	CCI cocoa breeding trial	4.47071	152.34088
27	SH	Kokopo–Vunamami	IPDM trial option 1	4.37841	152.29012
28	SH	Bitapaka	CCI on-farm trial (intermediate plot)	4.39615	152.35291
63	SH	Upper Sikut	On-farm trial—big hybrid plot	4.52317	152.21669
Autonomous Region of Bougainville					
8	CCI	Tsitato Constituency	Budwood garden (small clones)	5.41148	154.68005
9	SH	Hagogohe	Mangoana project	5.25598	154.70279
10	SH	Tsltalato Constituency	IPDM option 4 plot	5.35414	154.68344
11	SH	Peit Constituency	Pinu	5.23872	154.62741
12	SH	Teop Tonita Constit.	IPDM option 2 plot	5.54412	155.04445
13	SH	Teop Tonita Constit.	IPDM option 1 plot	5.54037	155.04636
14	PL	Rau		5.87129	155.23348
15	SH	Kokoda Constit.	Kiritana	6.49049	155.87463
16	SH	North Naisio Constit.	Kometu	6.22337	155.49454
New Ireland province					
17	SH	Tikana		2.71515	150.93091
18	CCI	Kavieng Urban	Demonstration block	2.57072	150.81267
19	SH	Tikana		2.89076	151.25050
20	SH	Central New Ireland	Tavinkarat	3.13047	151.70842
21	SH	Central New Ireland	Besen	3.14358	151.72737
22	SH	West Coast Central	Sevepo	3.43161	151.92056
23	PL	West Coast Central	Block 88	3.43775	151.94957
24	PL	Namatanai	Block 1	3.50471	152.29390
25	SH	Namatanai	Malilon	3.68517	152.38042
Morobe province					
29	SH	Wampar	Bereb	6.71767	146.78975
30	SH	Wampar	Ngawapog	6.57708	146.74677

Table A1. (cont'd) Locations and names of cocoa sites surveyed and sampled

Site	Owner	Local level government	Name of block	°S[a]	°E[a]
Morobe province (cont'd)					
31	SH	Umi–Atzena	Kaput	6.27709	146.22078
32	PL	Wampar	Block 4	6.59064	146.67113
33	SH	Ahi	Block 1	6.65435	146.98814
34	SH	Ahi	Yusemba	6.63217	147.02057
Northern Province					
35	SH	Oro Bay (Ward 18)	Kikiri–Gona Station	8.62358	148.29237
36	SH	Urban	Aruro	8.80717	148.23363
37	SH	Kokoda	Ombite	8.93519	147.87784
38	SH	Higaturu (Ward II)	Oemhambo	8.82256	148.08994
39	SH	Oro Bay	Kaesusu	8.87997	148.45892
40	SH		Boikiki Plantation	9.10033	148.43575
Madang province					
41	SH	Sumkilba	IPDM option 3 plot	4.96270	145.76643
42	DPI	Karkar	CCI Budwood Garden	4.57105	145.91771
43	PL	Karkar	Block 2	4.54547	146.00470
44	SH	Almami		4.50768	145.40198
45	SH	Sumgilba	Lapdingtat	4.76746	145.47699
46	SH	Usino	Block 2—Sangupuna	5.63012	145.48174
47	SH	Usino	Mituwa–Aikas	5.43439	145.51981
48	SH	Trangogol	Matyau	5.34508	145.69875
East Sepik province					
49	SH	Turubu	Tems	3.63264	143.76485
50	SH	Angoram	Kablok Junction	4.00508	144.04460
51	SH	Marianbek	Galimo	3.91980	143.99702
52	SH	West Yangoru	Walein	3.70881	143.26439
53	SH	Numbo	Hembenjanka	3.68984	143.51683
54	SH	Albikes–Mamblik	Kaunoru	3.62961	143.03053
57	SH	Drekikir	Namulas	3.57891	142.76166
60	CCI	Boiken–Dagua	Demo Block	3.48980	143.48706
West Sepik province					
55	SH	Nuku Central	Semenumbo	3.67528	142.47949
56	SH	Palai	Nomongondon	3.59174	142.47165
58	SH	Aitape East	Kumnai	3.15627	142.29527
59	SH	Aitape East		3.36540	143.03770
Western Highlands province					
61	SH	Jimi	Damna	5.47972	144.55994
62	SH	Jimi	Kelngapai	5.48453	144.60078

CCI = a CCI trial; DPI = a Department of Primary Industry-owned block managed by CCI as a demonstration trial; IPDM = integrated pest and disease management; PL = plantation; SH = smallholder block
[a] Geographic coordinates of tree number 1 of the sampled plot

Table A2. Tenure, history and vegetation of sampled cocoa sites

Sites	Tenure[a]	Year first farmed	Year cocoa first planted	Year current stand planted	Spacing (m)	Shade trees[b]	Food crops	Legume ground-cover	Legume trees
East New Britain province									
1	State	1967	1972	2000	4×4	Gl,C	No	No	Yes
2	State	1967	1972	2000	4×4	Gl,C	No	No	Yes
3	Purch.	<1980	<1980	1998	4×2.5	Gl,C,Be	No	No	Yes
4	Lease	1980	1980	1999	4×3	Gl	No	No	Yes
5	State	–	–	–	–	–	–	–	–
6	–	–	–	–	–	Gl,Ba	Yes	No	Yes
7	Cust.	1951	>1951	1998	4×2.5	C,Be	No	No	No
26	State	1930s	1950s	2004	–	C,Gl	–	–	–
27	Cust.	<1960	1985	1991	4×4	C	No	No	No
28	Cust.	1970s	1998	1998	4×3.5	C	No	No	No
63	Purch.	1995	1998	1998	4×4	Z,R	No	No	–
Autonomous Region of Bougainville									
8	State	1960s	1960s	1997	4×3	Gl,C	No	No	Yes
9	Cust.	1957	1968	2000	4×4	Gl,C,Br,O	Yes	No	Yes
10	Cust.	>1943	1960s	1999	4×4	Gl,Ga	No	No	Yes
11	Cust.	1958	1970	1996	4×4	C	No	No	No
12	Purch.	1960	1970s	2000	4∞4	Gl,Ba,O	Yes	No	Yes
13	Cust.	1960	1976	2000	4×4	Z	No	Yes	No
14	Purch.	1950	1950s	1984	4×4	C	No	No	No
15	Purch.	1984	1985	2005	3.5×3.5	Gl,L	No	No	Yes
16	Cust.	1965	1978	1999	4×4	C	No	Yes	No
New Ireland province									
17	Purch.	<1981	1981	1981	4×4	Gl	Yes	Yes	Yes
18	State	–	–	–	4×4	Gl	No	No	Yes
19	Cust.	?	1960s	1989 or 99?	4×3	C	No	No	No
20	Cust.	1962	1967–68	1987	4×4	C,L	No	Yes	Yes
21	Purch.	1960s	1987	1987	4×4	Gl,Be,O	No	No	Yes
22	Purch.	1950–60s	1950–60s	1996	4×4	C,Ba,Be,Br	Yes	No	No
23	Cust.[c]	1950s	1950s	1988	4×4	C	No	No	No
24	Purch.	–	–	1989	4×3	Gl,C	No	No	Yes
25	Purch.	1985	1986	1986	3×2	Z	Yes	Yes	No
Morobe province									
29	Cust.	1980s	1980s	1999	4×4	C,Be	Yes	No	No
30	Cust.	1982	1983	1983	4×4	C,Be	Yes	No	No
31	Cust.	1980s	1990	1990	4×4	Gl,L	Yes	Yes	Yes
32	Purch.	<1986	1986	1986	4×2	C	No	Yes	No
33	Cust.	–	–	–	4×4	Gl	No	No	Yes
34	Purch.	1995	1996	1996	4×4	Gl	Yes	No	Yes

Table A2. (cont'd) Tenure, history and vegetation of sampled cocoa sites

Sites	Tenure[a]	Year first farmed	Year cocoa first planted	Year current stand planted	Spacing (m)	Shade trees[b]	Food crops	Legume ground-cover	Legume trees
Northern Province									
35	Cust.	1972	1985	1985	3×3	Gl,C	Yes	Yes	Yes
36	Cust.	<1982	1982	1999	4×4	Gl,C,Be	Yes	No	Yes
37	Cust.	2003	2006	2006	3×3	Gl	Yes	No	Yes
38	Cust.	1980s	1994	1994	4×3	Gl,Be	Yes	No	Yes
39	Cust.	1987	1987	1997	4×4	Gl,C	Yes	Yes	Yes
40	Cust.[c]	1910s	1970s	1970s	4×4	Gl	Yes	Yes	Yes
Madang province									
41	Cust.	1998	1998	1998	4×4	Gl	No	No	Yes
42	Purch.	–	–	2002	3×2	Gl	No	No	Yes
43	Purch.	–	<1980	<1980	4×4	C	No	Yes	No
44	Cust.	1996	1998	1998	4×4	C,Gl	No	No	Yes
45	Cust.	1963	1983	2000	4×4	C,Gl	Yes	No	Yes
46	Purch.	1995	1998–99	1998–99	4×4	Gl	Yes	No	Yes
47	Cust.	1989	1994	1994	4×4	R	No	No	No
48	Cust.	1984	2003	2003	4×8	C,Gl	Yes	Yes	Yes
East Sepik province									
49	Cust.	1950s	1992	1992	4×4	C,Be	No	No	No
50	Purch.	1983	1985	1985	4×4	Z	No	No	No
51	Purch.	1986	1987	1987	4×4	Gl	No	No	Yes
52	Cust.	1960s	2002	2002	4×4	Z	No	No	
53	Cust.	1969	1974	1974	4×4	L,Be	Yes	No	Yes
54	Cust.	1960s	2001	2001	4×4	Gl,L	No	No	Yes
57	Cust.	1960s	1996	1996	4×4	Gl	Yes	No	Yes
60	State	1975	1995	1995	4×4	Gl,L	No	No	Yes
West Sepik province									
55	Cust.	1970s	1986	1986	4×4	O,Gl	No	No	Yes
56	Cust.	1960s	1982	1982	4×4	L,Gl	No	No	Yes
58	Cust.	2000	2000	2000	4×4	C,Gl	No	No	Yes
59	Cust.	1988	1988	1988	6×6	C,Be	No	Yes	No
Western Highlands province									
61	Cust.	1970s	2001	2001	Variable	C,L,Ba,O	–	No	Yes
62	Cust.	–	1984	–	–	–	–	–	–

– = not recorded
[a] State land, purchased (Purch.), leased from the government (Lease) or customary land (Cust.)
[b] Banana (Ba), betel nut (Be), breadfruit (Br), coconut (C), galip (Ga), *Gliricidia* (Gl), leucaena (L), other fruit or nut trees including pau, aila, balbal, penats, mango (O), bush regrowth (R) or no shade (Z)
[c] Originally purchased for plantation but currently in the hands of customary owners.

Table A3. Reasons given for good or poor yields

Site[a]	Satisfied?	Reasons given by grower for good or poor yield
East New Britain province		
3	Yes	Missing trees, swampy area, knowledge
4 (P)	Yes	Good management, fertiliser, clones
7	Yes	Land shortage, theft, knowledge, management
26	Yes	Management, planting materials, soil
27	No	Limited labour, other commitments, fertiliser and tools shortage, theft of ripe pods
28	No	Knowledge of cocoa husbandry, lacking good management practices
63	No	Poor management, pruning, maybe fertiliser
Autonomous Region of Bougainville		
8	No	Limited funding
9	No	Limited knowledge, inadequate labour, fertiliser and chemicals
10	No	Pests from neighbouring farms
11	No	Labour cost high (4 children all elsewhere), theft, poor management, maybe soil exhaustion
12	No	Old material (Trinitario), labour limited, access to credit to purchase inputs
13	No	Bad management, finance to purchase tools materials, soils exhausted, areas waterlogged
14 (P)	No	Senile cocoa, bad management, lack of knowledge of new IPDM technology
15	Yes	No fertiliser and chemicals limit increase in yield, labour expensive
16	No	Management, location, competition with coconut
New Ireland province		
17	Yes	[No reasons given]
18	Yes	[No reasons given]
19	Not sure	No records due to family members harvesting beans without grower's knowledge
20	No	Low management input, require training on block management, require block rehabilitation
21	No	No proper management, require training on block management
22	No	
23 (P)	No	Lack of new planting materials, very old cocoa stands (19 years), management needs to be updated
24 (P)	No	Old trees, knowledge (lack of new update of technology), maybe due to lack of soil nutrient factors
25	No	Poor maintenance, cocoa dryer inoperable, rain and wind destroying flowers, family labour, birds a pest
Morobe province		
29	No	Black pod disease, production per tree is low, lacking good management
30	No	Other commitments, price rise in vanilla in the past, knowledge lacking on good management
31	No	Pests and diseases (e.g. black pod, rats, longicorn), lack knowledge on good management, change in price
32 (P)	No	Poor maintenance, pests and diseases (e.g. termites, black pod), previous waterlogging, close spacing
33	No	Fermentary capacity not sufficient, no pruning, not enough labour, pests and diseases (e.g. black pod)
34	No	Labour dispute, lacking of knowledge on good management, fermentary capacity not sufficient

Table A3. (cont'd) Reasons given for good or poor yields

Site[a]	Satisfied?	Reasons given by grower for good or poor yield
Northern Province		
35	No	Price is low in town, lack of extension services, limited assistance from government
36	No	Soil not suitable in valley, pests and diseases, not enough shade, big area but less labour
37	No	Few trees bearing with more yet to bear, knowledge on good management, black pod
38	No	Pests and diseases, lack of knowledge, limited assistance, need nursery
39	No	Limited supply of new planting material, lack of good management practices
40	No	Pests and diseases, poor management, lack of tools, limited labour, fermentery and dryer in bad condition
Madang province		
41	No	Lack knowledge on good management, other commitments apart from cocoa
42	No	Thieves, black pod
43 (P)	No	Missing trees, thieves, some areas of plantation stony
44	Yes	Adequate labour, good planting materials, no land disputes, experience as plantation manager
45	Yes	Knowledge acquired as a CCI contact farmer, sufficient family labour, good access, no land dispute
46	Yes	IPDM technology, sufficient labour, three recruited and three family members, good materials, good access
47	No	Probably low soil fertility, poor planting material, lack of skills and knowledge on management
48	Yes	Good management, good experience as farmer and Department of Primary Industry officer, good access, no land dispute
East Sepik province		
49	Yes	Good road access to market, no land dispute, only family labour
50	No	Old planting materials, lack of knowledge and skills, poor management, limited labour
51	No	Lack of knowledge on husbandry, limited labour, insufficient planting material, no use of fertiliser
52	Yes	New planting, good family labour, easy market access
53	No	Very old planting materials, poor management, no extension of new knowledge
54	No	Lacks cocoa skills, unrecommended planting material, no fertiliser application
57	No	Lack skills and knowledge on establishment and management, poor planting material, no fertiliser used
60	Yes	Adequate labour, good management, recommended planting material, good knowledge
West Sepik province		
55	No	Very old planting materials, no fertiliser application, poor management, lacks skills and knowledge
56	No	Limited labour, old planting materials, no fertiliser application, low block management
58	No	Frequent flooding, low price, limited knowledge on management, no fertiliser
59	No	Limited knowledge on management, committed to other obligations, no fertiliser used
Western Highlands province		
61	No	No poor market access

[a] Sites on CCI trials have been omitted and plantation blocks are indicated with a (P).

Table A4. Management and incidence of diseases

Site number	Tree health and block management scores				Disease score			
	Tree health	Shade	Weeding	Pruning	Black pod	Canker	VSD	Pink disease
East New Britain province								
1	G	VG	G	G	L	L	L	N
2	G	VG	VG	G	L	N	L	N
3	G	A	G	G	M	L	L	L
4	G	VG	VG	VG	L	L	L	L
5		G	G	A	M	N	L	N
6	A	G	A	A	L	L	L	L
7	G	G	G	G	L	L	L	L
26	G	G	G	G	L	L	L	N
27	A	A	A	P	L	L	N	N
28	G	A	A	A	L	L	L	N
63	G	P	G	A	L	L	L	L
Autonomous Region of Bougainville								
8		G	G	G	L	L	L	N
9	A	A	A	G	L	L	N	M
10	G	A	G	G	L	L	N	L
11	A	A	A	A	M	N	L	M
12	G	A	G	A	L	L	L	L
13	A	VP	A	P	M	L	L	L
14	P	P	P	P	S	M	N	M
15	P	P	G	A	L	L	N	L
16	G	G	A	A	L	L	N	N
New Ireland province								
17	P	VP	VP	P	S	L	N	L
18	G	A	G	G	L	L	N	L
19	A	A	P	P	L	L	N	M
20	P	P	P	VP	S	L	N	L
21	G	A	G	A	L	L	N	L
22		A	A	A	L	N	N	L
23	A	A	A	A	M	L	N	L
24	A	P	A	A	M	L	N	L
25	A	A	P	P	M	M	N	L
Morobe province								
29	G	A	A	P	M	L	N	N
30	A	A	A	P	L	L	N	N
31	G	A	G	A	L	L	M?	L
32	G	G	G	A	L	L	L	N

Table A4. (cont'd) Management and incidence of diseases

Site number	Tree health and block management scores				Disease score			
	Tree health	Shade	Weeding	Pruning	Black pod	Canker	VSD	Pink disease
Morobe province (cont'd)								
33	A	P	G	VP	S	L	N	N
34	G	A	A	A	M	L	N	N
Northern Province								
35	P	P	P	P	M	L	N	L
36	A	A	G	A	M	L	M	M
37	G	G	G	G	N	N	N	N
38	P	P	P	P	S	S	M	M
39	G	A	A	A	L	L	N	L
40	A	P	P	P	M	M	N	N
Madang province								
41	G	VG	G	G	L	L	L	L
42	G	G	G	G	N	L	L	L
43	A	P	P	P	L	L	L	L
44	G	G	G	A	L	L	L	L
45	G	P	P	P	L		L	N
46	VG	G	VG	G	L	L	N	N
47	P	VP	VP	VP	M	L	M	L
48	G		A	G	L	L	N	N
East Sepik province								
49	A	P	VP	VP	M	M	N	L
50	G	P	A	VP	M	M	L	M
51	A	P	A	P	L	L	L	N
52	G	P	A	VP	M	L	L	L
53	A	P	P	P	L	L	L	N
54	G	P	A	A	L	L	L	N
57	G	P	A	P	L	L	L	N
60	G	A	G	G	N	L	N	N
West Sepik province								
55	A	VP	VP	VP	M	M	M	M
56	P	A	A	P	M	M	M	L
58	G		A	A	L	L	N	N
59	A	A	P	VP	M	L	N	N
Western Highlands province								
61	G	G	G	A	L	N	N	L

A = average; G = good; L = low; M = moderate; N = none; P = poor; S = severe; VG = very good; VP = very poor; VSD = vascular streak disease
Note: Scores were assessed on the sampled plots.

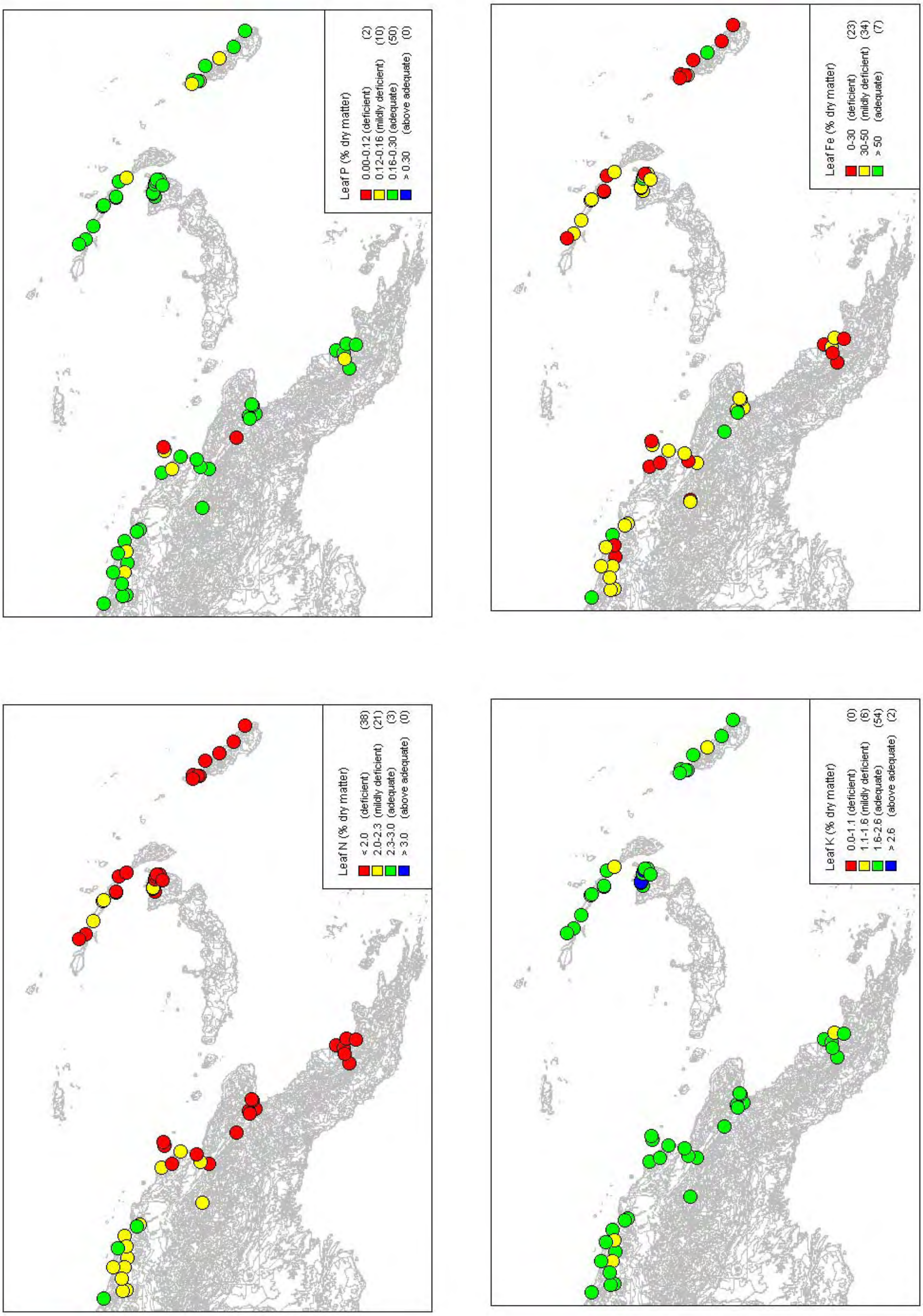
Table A5. Cocoa pod analyses

Element	Site 4	Site 63	Site 8	Site 18	Site 25	Site 34	Site 35	Site 44	Mean
	ENBP	ENBP	ARB	NIP	NIP	MoP	NP	MaP	
Beans									
Nitrogen	1.9	2.2	2.0	2.3	2.2	1.9	2.4	2.2	2.12
Potassium	1.46	1.21	1.26	1.59	1.20	1.51	1.19	1.22	1.33
Calcium	1,350	950	1,300	1,630	1,240	1,080	1,080	1,210	1,230
Magnesium	3,300	3,100	3,900	3,500	3,300	3,300	3,300	3,400	3,388
Phosphorus	4,900	4,900	5,200	5,400	3,600	5,000	4,700	5,300	4,875
Sulfur	1,310	1,260	1,490	1,330	1,520	1,320	1,360	1,260	1,356
Zinc	40	1,530	75	870	590	2,800	2,200	5,800	1,738
Iron	32	33	28	32	37	35	36	55	36
Manganese	16	24	28	39	19	29	22	19	24
Boron	20	20	24	19	22	18	30	24	22
Copper	15	38	29	37	36	37	16	33	30
Molybdenum	<0.8	<0.8	<0.8	<0.8	<0.8	<0.7	<0.8	<0.8	<0.8
Cobalt	<0.7	1.5	<0.7	0.80	0.90	1.0	<0.7	<0.7	1.1
Nickel	<0.8	2.1	0.89	1.6	2.2	2.5	9.6	11	4.3
Sodium	<0.4	49	<0.4	<0.4	<0.4	<0.4	1.9	1.2	17.5
Aluminium	0.60	5.0	<0.1	2.1	1.9	11	11	13	6.4
Titanium	<0.1	0.11	<0.1	0.19	0.25	0.49	0.52	0.36	0.3
Chromium	<0.5	<0.5	<0.5	<0.5	<0.5	1.2	0.70	1.0	1.0
Cadmium	<0.2	<0.2	0.28	1.0	<0.2	0.28	<0.2	<0.2	0.5
Selenium	<7	<7	<7	<7	<7	<7	<7	<7	<7
Lead	<2	<2	<2	<2	<2	<2	<2	<2	<2

Table A5. (cont'd) Cocoa pod analyses

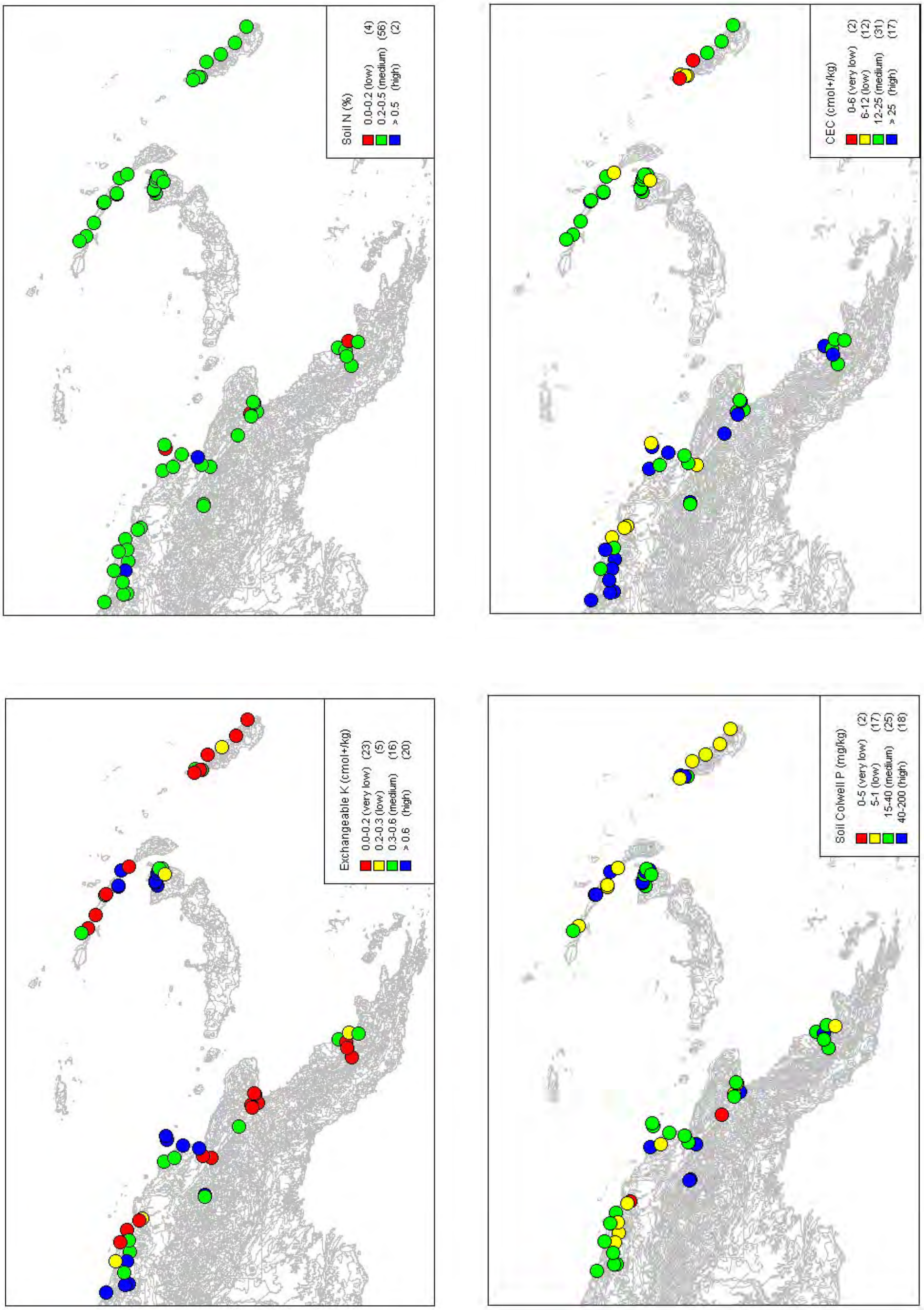
Element	Site 4	Site 63	Site 8	Site 18	Site 25	Site 34	Site 35	Site 44	Mean
	ENBP	ENBP	ARB	NIP	NIP	MoP	NP	MaP	
Husks									
Nitrogen	0.94	0.97	0.88	1.1	1.2	1.0	1.2	1.0	1.04
Potassium	3.8	3.6	4.3	3.5	3.3	3.5	4.2	3.7	3.74
Calcium	3,800	4,600	4,500	4,700	3,700	3,400	4,900	5,200	4,350
Magnesium	1,570	2,300	2,400	1,960	2,500	2,500	3,100	3,300	2,454
Phosphorus	1,450	1,330	1,260	1,400	840	1,620	1,420	1,700	1,378
Sulfur	1,570	1,520	1,630	1,530	1,810	850	790	1,630	1,416
Zinc	33	56	56	54	95	56	37	72	57
Iron	18	17	22	17	20	17	19	21	19
Manganese	13	54	48	61	25	66	41	29	42
Boron	21	26	27	20	26	20	47	29	27
Copper	5.9	16	10	16	18	18	6.1	17	13
Molybdenum	<0.8	<0.8	<0.7	<0.8	<0.8	<0.7	<0.8	<0.8	<0.8
Cobalt	<0.7	1.7	<0.7	1.1	<0.7	1.1	<0.7	<0.7	1.3
Nickel	<0.8	<0.8	<0.8	<0.8	<0.8	1.3	1.6	7.8	3.6
Sodium	<0.4	<0.4	0.73	<0.4	<0.4	<0.4	<0.4	<0.4	0.7
Aluminium	5.5	5.0	<0.1	<0.1	2.3	<0.1	7.7	7.2	5.5
Titanium	0.48	0.20	<0.1	<0.1	0.27	<0.1	0.21	0.68	0.4
Chromium	<0.5	<0.5	<0.4	<0.5	<0.5	<0.4	<0.5	<0.5	<0.5
Cadmium	<0.2	<0.2	0.29	0.94	<0.2	0.44	<0.2	<0.2	0.6
Lead	<2	<2	<2	<2	<2	<2	<2	<2	<2
Selenium	<7	<7	<7	<7	<7	<7	<7	<7	<7

ARB = Autonomous Region of Bougainville; ENBP = East New Britain province; ESP = East Sepik province; MaP = Madang province; MoP = Morobe province, NIP = New Ireland province; NP = Northern Province; WHP = Western Highlands province; WSP = West Sepik province
Note 1: Values are in milligrams/kilogram dry matter, except for nitrogen and potassium, which are in % dry matter.
Note 2: High zinc and titanium concentrations suggest contamination of bean samples (most probably from galvanised iron trays used for drying) at all sites except 4 and 8.



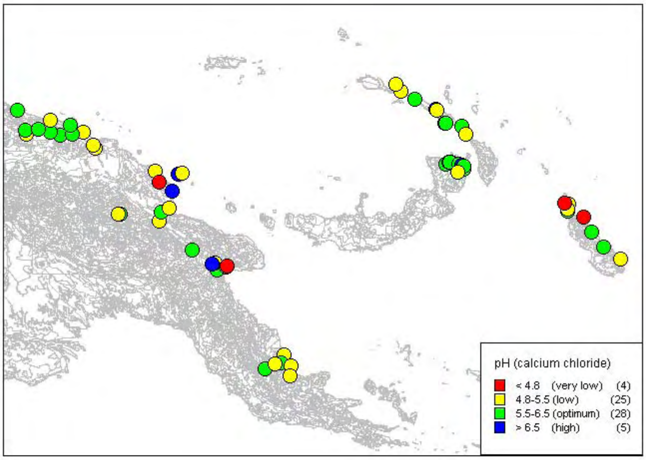
CEC = cation exchange capacity; cmol+ = centimoles of positive charge; Fe = iron; K = potassium; kg = kilogram; mg = milligram; N = nitrogen; P = phosphorus

Figure A1. Maps of leaf N, P, K and Fe contents and soil (0–0.15 m depth) exchangeable K, total N and Colwell P contents, cation exchange capacity (CEC) and pH for the surveyed blocks



CEC = cation exchange capacity; cmol+ = centimoles of positive charge; Fe = iron; K = potassium; kg = kilogram; mg = milligram; N = nitrogen; P = phosphorus

Figure A1. (cont'd) Maps of leaf N, P, K and Fe contents and soil (0–0.15 m depth) exchangeable K, total N and Colwell P contents, cation exchange capacity (CEC) and pH for the surveyed blocks



CEC = cation exchange capacity; cmol+ = centimoles of positive charge; Fe = iron;
K = potassium; kg = kilogram; mg = milligram; N = nitrogen; P = phosphorus

Figure A1. (cont'd) Maps of leaf N, P, K and Fe contents and soil (0–0.15 m depth) exchangeable K, total N and Colwell P contents, cation exchange capacity (CEC) and pH for the surveyed blocks

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